Oznámení: Proseminář jaderné a subjaderné fyziky,
každé Úterý od 9:00 Troja, 9.patro

Přednáška 4.

Přirozená radioaktivita, využití pro datování

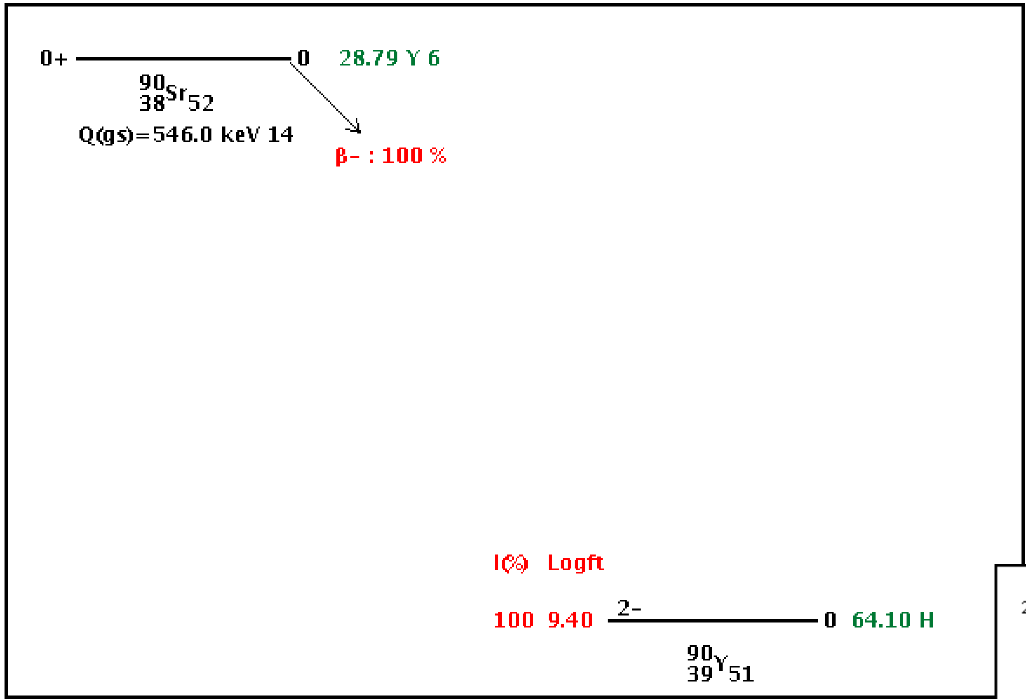
Kinematika, Mandelstamovy proměnné,

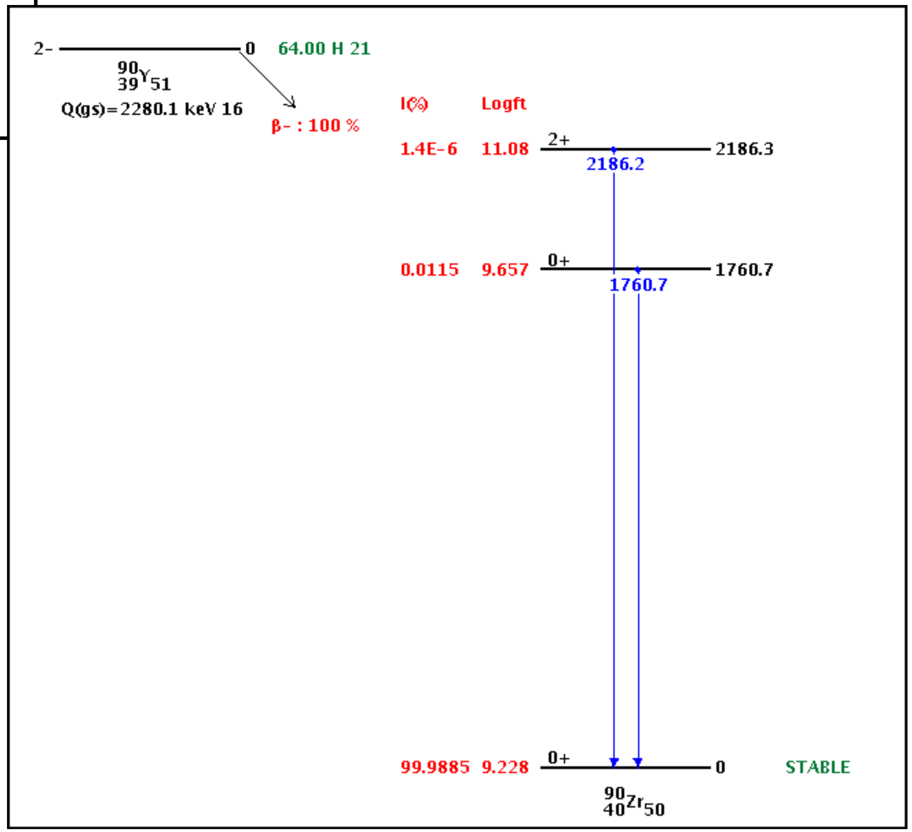
Gama přechody, použití

Interakce jaderného záření s prostředím

Účinky radiace

Příiklad beta zářiče





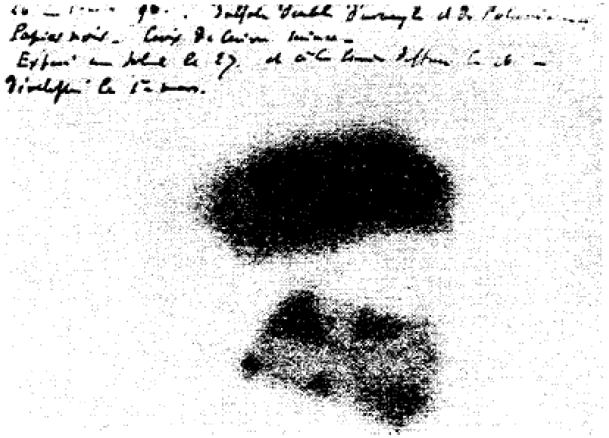
$$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + e^- + \overline{\nu}_e \qquad T_{1/2} = 28{,}8\,years$$

$$^{90}_{39}Y \rightarrow ^{90}_{40}Zr + e^- + \overline{\nu}_e \qquad T_{1/2} = 64{,}1\,hod.$$

Objev přirozené radioaktivity:

Antoine Henri Becquerel – objevil, že uranové soli produkují pronikavé záření

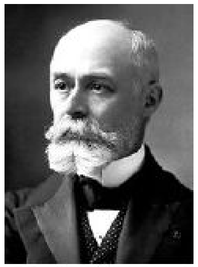
Marie a Pierre Curie zkoumali toto záření a Marie vyřešila záhadu chybějících prvků mezi Bi a U, jako první izolovala Radium a Polonium ve smolinci (pitchblende) z Jáchymova



The Nobel Prize in Physics 1903

"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"

"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"



Antoine Henri Becquerel

1/2 of the prize

France

École Polytechnique
Paris, France

b. 1852
d. 1908

Pierre Curie

1/4 of the prize

France

École municipale de physique et de chimie industrielles (Municipal School of Industrial Physics and Chemistry)
Paris, France

b. 1859
d. 1906

Marie Curie, née Sklodowska

1/4 of the prize

France

b. 1867
(in Warsaw, Poland, then Russian Empire)
d. 1934

The Nobel Prize in Chemistry 1911

"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"

Marie Curie, née Sklodowska

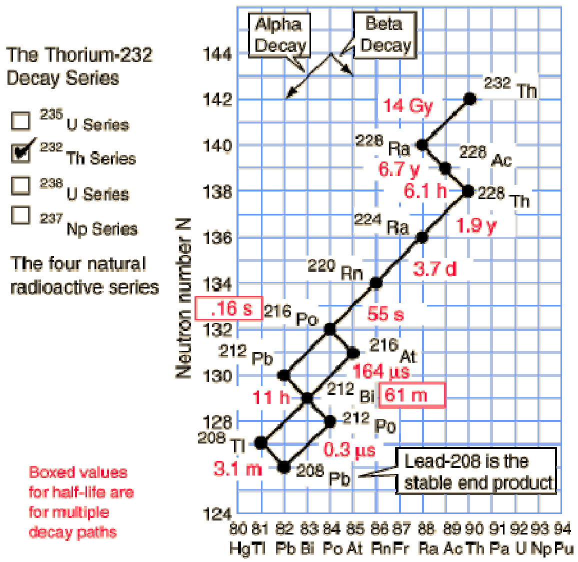
France

Sorbonne University
Paris, France

b. 1867
(in Warsaw, Poland, then Russian Empire)
d. 1934

Pierre Curie: „It can even be thought that radium could become very dangerous in criminal hands, and here the question can be raised whether mankind benefits from knowing the secrets of Nature, whether it is ready to profit from it or whether this knowledge will not be harmful for it. The example of the discoveries of Nobel is characteristic, as powerful explosives have enabled man to do wonderful work. They are also a terrible means of destruction in the hands of great criminals who are leading the peoples towards war. I am one of those who believe with Nobel that mankind will derive more good than harm from the new discoveries.“

Rozpadové řady:



Thoriová:

$Mod(A,4)=0:\quad {}^{232}_{90}Th \rightarrow ... \rightarrow {}^{208}_{82}Pb \quad T_{1/2}=13{,}9\cdot 10^{9}\ years$

Neptuniová:

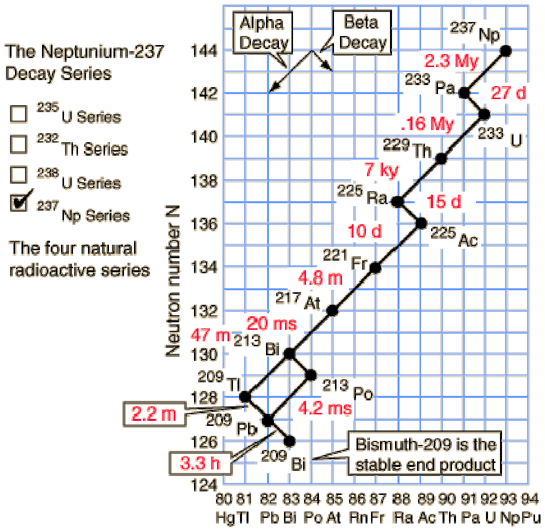
$Mod(A,4)=1:\quad {}^{237}_{93}Np \rightarrow ... \rightarrow {}^{209}_{83}Bi \quad T_{1/2}=0{,}00255\cdot 10^{9}\ years$

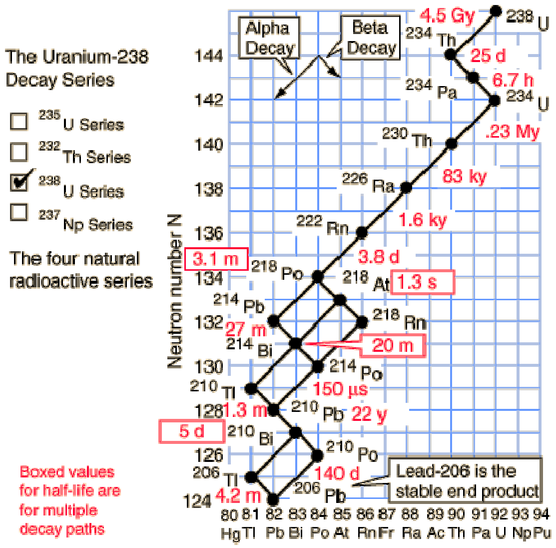
Uranová:

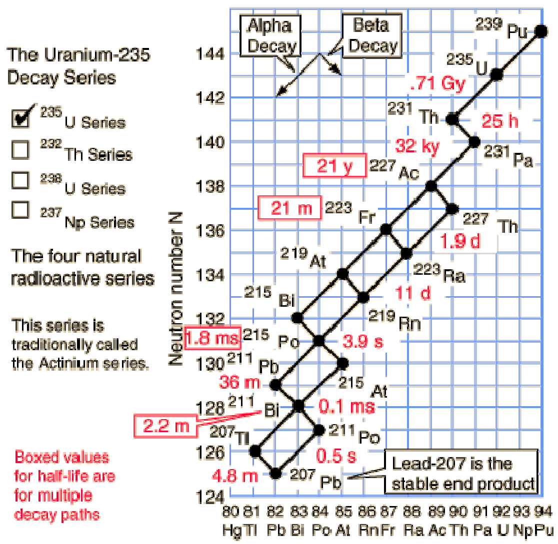
$Mod(A,4)=2:\quad {}^{238}_{92}U \rightarrow ... \rightarrow {}^{206}_{82}Pb \quad T_{1/2}=4{,}51\cdot 10^{9}\ years$

Aktiniová:

$Mod(A,4)=3:\quad {}^{235}_{92}U \rightarrow ... \rightarrow {}^{207}_{82}Pb \quad T_{1/2}=0{,}707\cdot 10^{9}\ years$

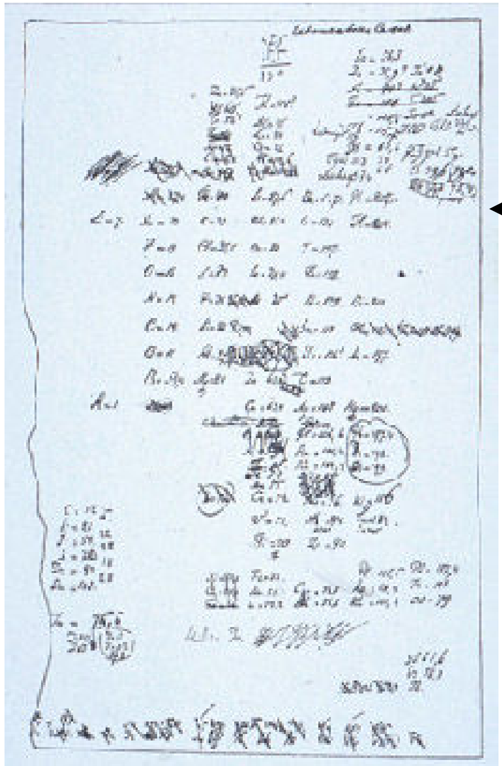






Periodická tabulka prvků

Mendelejev 1869



			Ti=50	Zr=90	?=180
			V=51	Nb=94	Ta=182
			Cr=52	Mo=96	W=186
			Mn=55	Rh=104.4	Pt=197.4
			Fe=56	Ru=104.4	Ir=198
			Ni=Co=59	Pd=106.6	Os=199
H=1			Cu=63.4	Ag=108	Hg=200
	Be=9.4	Mg=24	Zn=65.2	Cd=112	
	B=11	Al=27.4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79.4	Te=128?	
	F=19	Cl=35.5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85.4	Cs=133	Tl=204
		Ca=40	Sr=87.6	Ba=137	Pb=207
		?=45	Ce=92		
		?Er=56	La=92		
		?Yt=60	Di=95		
		? In=75.6	Th=118?		

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 1																	He 2
2	Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
3	Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
6	Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
7	Fr 87	Ra 88	Ac 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Uub 112	Uut 113	Uuq 114	Uup 115	Uuh 116	Uus 117	Uuo 118

6	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
7	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

Datování pomocí radioaktivních rozpadů

Isotopes of Uranium (Z=92)

Click on an isotope to get more information about its decay

Isotope	Half-life	Spin Parity	Decay Mode(s) or Abundance
^{218}U	1.5 ms	0+	%A=100
^{219}U	42 us		%A=?
^{220}U			
^{221}U			
^{222}U	1.0 us	0+	%A=100
^{223}U	18 us		%A=?
^{224}U	0.9 ms	0+	%A=100
^{225}U	95 ms		%A=100
^{226}U	0.35 s	0+	%A=100
^{227}U	1.1 m	(3/2+)	%A=100, %EC+%B+ < 0.001
^{228}U	9.1 m	0+	%EC<5, %A>95
^{229}U	58 m	(3/2+)	%EC+%B+ ~ 80, %A ~ 20
^{230}U	20.8 d	0+	%A=100, %SF < 1.4E-10
^{231}U	4.2 d	(5/2-)	%EC=100, %A ~ 0.0055
^{232}U	68.9 y	0+	%A=100, %24NE=9E-11 7
^{233}U	1.592e+5 y	5/2+	%A=100, %SF < 6E-11, %24NE < 9.5E-11
^{234}U	2.455e+5 y	0+	%Abundance=0.0055 5, %A=100, %SF=1.64E-9 22, %NE=9E-12 7, %MG=1.4E-11 3
^{235}U	7.038e+8 y	7/2-	%Abundance=0.7200 12, %A=100, %SF=7.0E-9 21, %20NE=8E-10 4
$^{235m1}U$	25 m	1/2+	%IT=100
^{236}U	2.342e7 y	0+	%A=100, %SF=9.4E-8 4
^{237}U	6.75 d	1/2+	%B-=100
^{238}U	4.468e+9 y	0+	%Abundance=99.2745 60, %A=100, %SF=5.45E-5 7, %BB=2.2E-10 7
$^{238m1}U$	225 ns	0+	
$^{238m2}U$	1 ns		
^{239}U	23.45 m	5/2+	%B-=100
^{240}U	14.1 h	0+	%B-=100
^{241}U			
^{242}U	16.8 m	0+	%B-=100

Zjednodušený příklad:

$$N_{235}(t) = N_{235}(0)\cdot e^{-\frac{t}{T_{235}/\ln(2)}}$$

$$N_{238}(t) = N_{238}(0)\cdot e^{-\frac{t}{T_{238}/\ln(2)}}$$

$$\frac{N_{235}(t)}{N_{238}(t)} = \frac{N_{235}(0)}{N_{238}(0)} e^{-\left(\frac{1}{T_{235}/\ln(2)}-\frac{1}{T_{238}/\ln(2)}\right)t}$$

$$\frac{0.7\%}{99.3\%} = 1\cdot e^{-\left(\frac{1}{0,70\cdot 10^9[y]/\ln(2)}-\frac{1}{4,47\cdot 10^9[y]/\ln(2)}\right)t[y]}$$

$$t = 5,97\cdot 10^9\, y$$

Uran.nb

Určování stáří hornin

Metoda Uran-Olovo

	miliardy let	
^{238}U	4.468	^{206}Pb
^{235}U	0.704	^{207}Pb
^{40}K	1.251	^{40}Ar
^{87}Rb	48.8	^{87}Sr

-V uranových dolech: olovo vzniklo z uranu, nebzlo tam žádné na začátku, protože se chemicky nesnese s uranem

-Stáří Země určeno jako 4,2 miliardy let.

Metoda Rubidium-Stroncium

Metoda Rubidium-Stroncium

$$^{86}_{38}Sr$$

$$^{87}_{37}Rb \rightarrow ^{87}_{38}Sr + e^- + \bar{\nu}_e \qquad T_{1/2} = 46{,}8\cdot 10^9\, y$$

$$t=0: \left(\frac{^{87}_{38}Sr}{^{86}_{38}Sr}\right)_{t=0} ; \left(\frac{^{87}_{37}Rb}{^{86}_{38}Sr}\right)_{t=0}$$

$$\left(\frac{^{87}_{37}Rb}{^{86}_{38}Sr}\right)_t = \frac{\left(^{87}_{37}Rb\right)_{t=0}\cdot e^{-\frac{t}{T_{1/2}/\ln(2)}}}{\left(^{86}_{38}Sr\right)_{t=0}} = \left(\frac{^{87}_{37}Rb}{^{86}_{38}Sr}\right)_{t=0} \cdot e^{-\frac{t}{T_{1/2}/\ln(2)}}$$

$$\left(\frac{^{87}_{38}Sr}{^{86}_{38}Sr}\right)_t = \frac{\left(^{87}_{38}Sr\right)_{t=0} + \left(^{87}_{37}Rb\right)_{t=0}\cdot\left(1-e^{-\frac{t}{T_{1/2}/\ln(2)}}\right)}{\left(^{86}_{38}Sr\right)_{t=0}} =$$

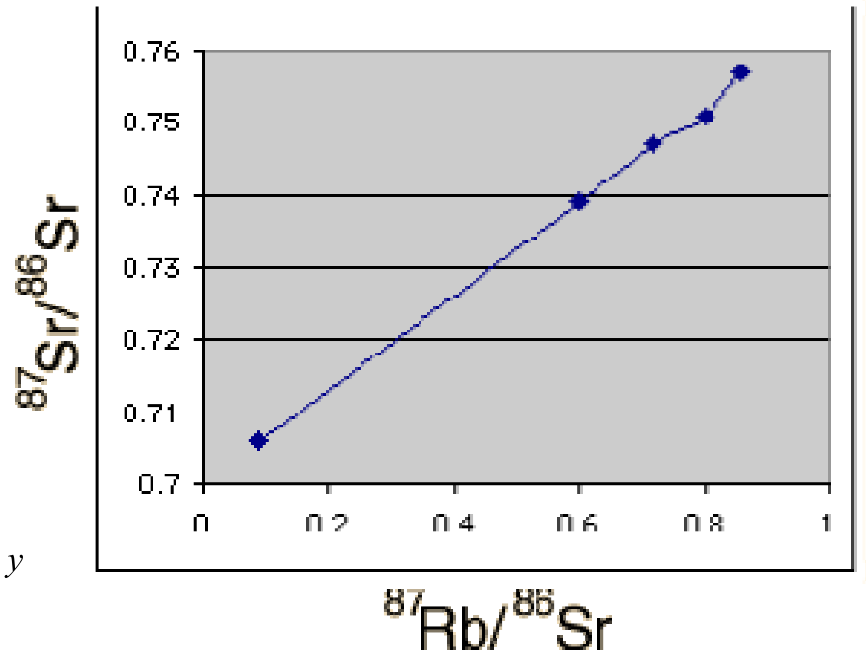
$$\frac{\left(^{87}_{38}Sr\right)_{t=0} + \left(^{87}_{37}Rb\right)_{t=0}\cdot e^{-\frac{t}{T_{1/2}/\ln(2)}}\cdot\left(e^{\frac{t}{T_{1/2}/\ln(2)}}-1\right)}{\left(^{86}_{38}Sr\right)_{t=0}} =$$

$$\left(\frac{^{87}_{38}Sr}{^{86}_{38}Sr}\right)_{t=0} + \left(\frac{^{87}_{37}Rb}{^{86}_{38}Sr}\right)_{t=0}\cdot\left(e^{\frac{t}{T_{1/2}/\ln(2)}}-1\right)$$

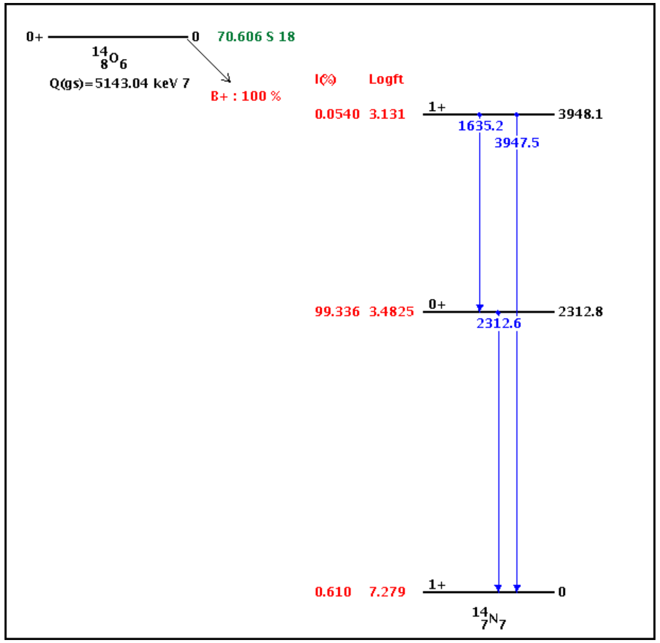
$$\left(e^{\frac{t}{T_{1/2}/\ln(2)}}-1\right) = \frac{0{,}049}{0{,}77} \Rightarrow t = \frac{T_{1/2}=46{,}8\cdot 10^9\, y}{\ln(2)}\ln\left(1+\frac{0{,}049}{0{,}77}\right) = 4{,}17\cdot 10^9\, y$$

Meteorit	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Modoc	0.86Sr	0.757
Homestead	0.8Sr	0.751
Bruderheim	0.72Sr	0.747
Kyushu	0.6Sr	0.739
Buth Furnace	0.09Sr	0.706

4.6 x 10^9 years



Radioaktivní izotopy vznikající v atmosféře působením kosmického záření:

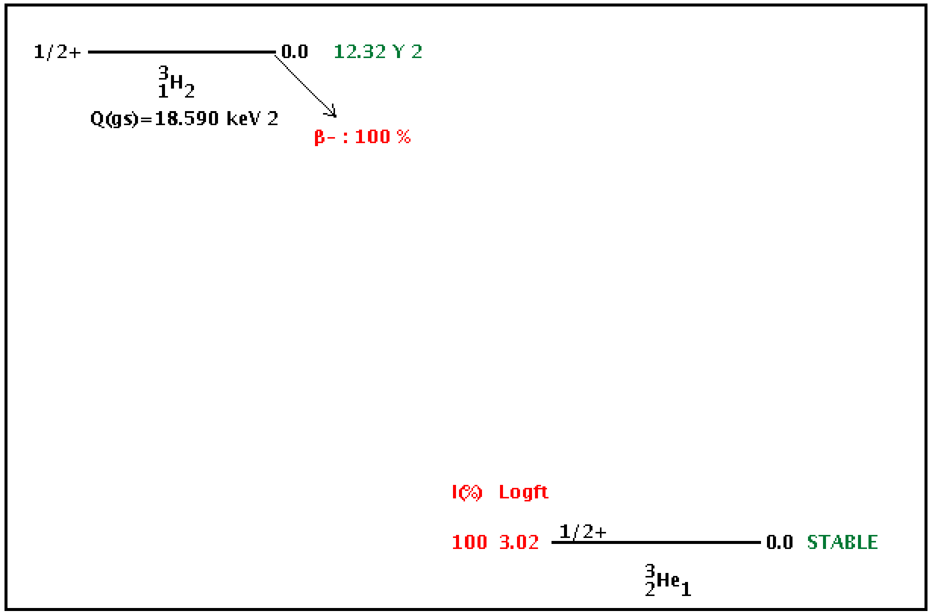


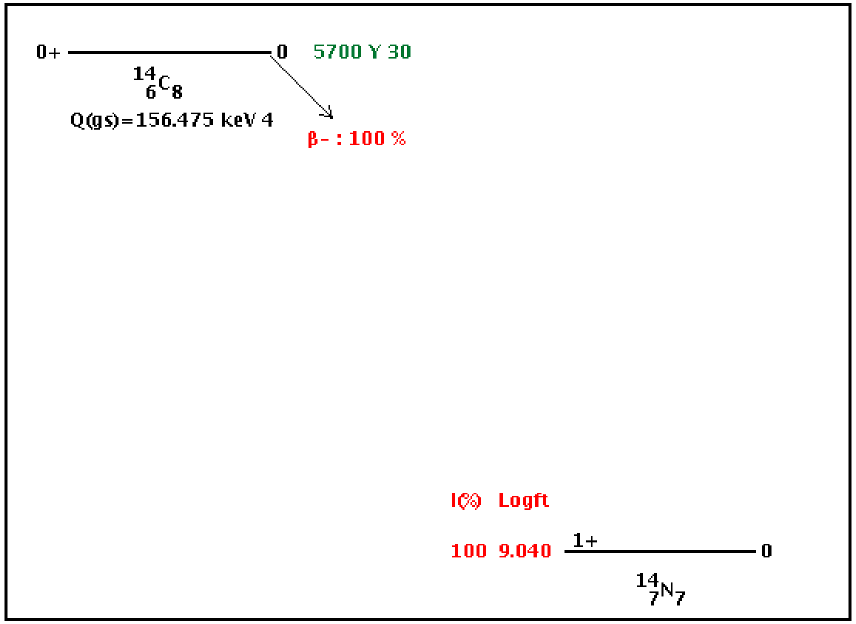
$$^{1}_{1}p+^{16}_{8}O\rightarrow ^{14}_{6}C+3\ ^{1}_{1}H$$

$$^{1}_{1}p+^{16}_{8}O+^{1}_{1}p\rightarrow ^{14}_{8}O+\ ^{3}_{1}H$$

$$^{1}_{0}p+^{14}_{7}N\rightarrow ^{12}_{6}C+\ ^{3}_{1}H$$

$$^{1}_{0}p+^{14}_{7}N\rightarrow ^{14}_{6}C+\ ^{1}_{1}H$$

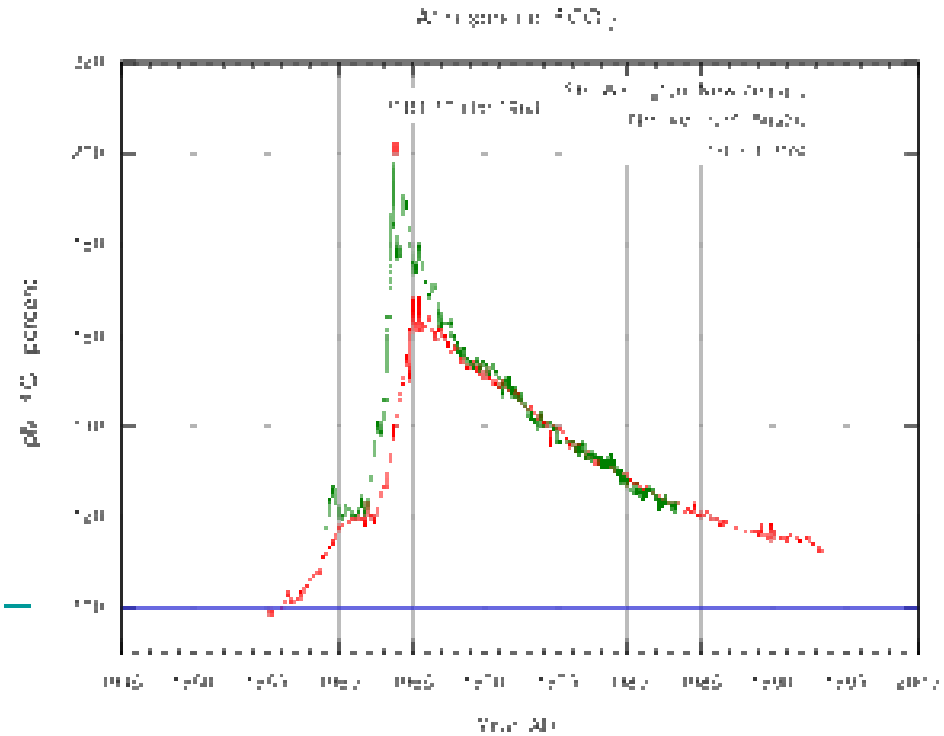




Datování stáří živých organismů pomocí uhlíku 14

-Uhlík 14 tvoří CO2 a ten se dostává do zelených rostlin
-Živočichové, kteří se živí zelenými rostlinami a-nebo jinými živočichy,
kteří pojídají zelenou stravu dostávají do těla C14, ten je v rovnováze s C12
-Jakmile umřou, začne se obsah C14 v jejich tělech snižovat

Je třeba brát do úvahy změny obsahu uhlíku 14 v atmosféře



Atmospheric ^{14}C, New Zealand[1] and Austria[2]. The New Zealand curve is representative for the Southern Hemisphere, the Austrian curve is representative for the Northern Hemisphere. Atmospheric nuclear weapon tests almost doubled the concentration of ^{14}C in the Northern Hemisphere [3].

Kinematika – 4 vektory

$4-vektor$

$(V_0,\vec{V})=(V_0,V_x,V_y,V_z)$

$V_0 \rightarrow \gamma(V_0-\beta V_x)$

$\vec{V}$

$V_x \rightarrow \gamma(V_x-\beta V_0)$

Součin dvou 4-vektorů:

$P\cdot Q = P_0Q_0-\vec{P}\cdot\vec{Q}$ Součin dvou 4-vektorů je invariantní při Lorentzově transformaci:

$$P\cdot Q \rightarrow \gamma(P_0-\beta P_x)\gamma(Q_0-\beta Q_x)-\gamma(P_x-\beta P_0)\gamma(Q_x-\beta Q_0)-P_yQ_y-P_zQ_z=$$

$$P_0Q_0(\gamma^2-\gamma^2\beta^2)+P_0Q_x(-\gamma^2\beta+\gamma^2\beta)+P_xQ_0(-\gamma\beta^2+\gamma\beta^2)-P_xQ_x(-\gamma^2\beta^2+\gamma^2)-P_yQ_y-P_zQ_z=$$

$$P_0Q_0(\gamma^2-\gamma^2\beta^2)-P_xQ_x(\gamma^2-\gamma^2\beta^2)-P_yQ_y-P_zQ_z=P_0Q_0-P_xQ_x-P_yQ_y-P_zQ_z=P\cdot Q$$

Příkladem 4-vektoru je:

$(ct,\vec{r})$

4-vektor energie a hybnosti, 4-impuls:

$$P=(E,\vec{p})$$

$$P\cdot P=E\cdot E-\vec{p}\cdot\vec{p}=E^2-p^2=M^2$$

Použití 4-hybností pro výpočet prahu reakcí. Příklad - objev antiprotonu

$$p + p \to p + p + p + \overline{p}$$

$$(E, \vec{p}) + (m_p, \vec{0}) = (\sum_{i=1}^{4} E_i, \sum_{i=1}^{4} \vec{p}_i)$$

$$P_{init} = (E + m_p, \vec{p})$$

$$P^2{}_{init} = (E + m_p)^2 - \left|\vec{p}\right|^2 = E^2 - \left|\vec{p}\right|^2 + m^2{}_p + 2m_p E = 2m^2{}_p + 2m_p E$$

$$P_{thr} = (\sum_{i=1}^{4} m_i, \vec{0}) = (4m_p, \vec{0})$$

$$P^2{}_{thr} = 16m^2{}_p$$

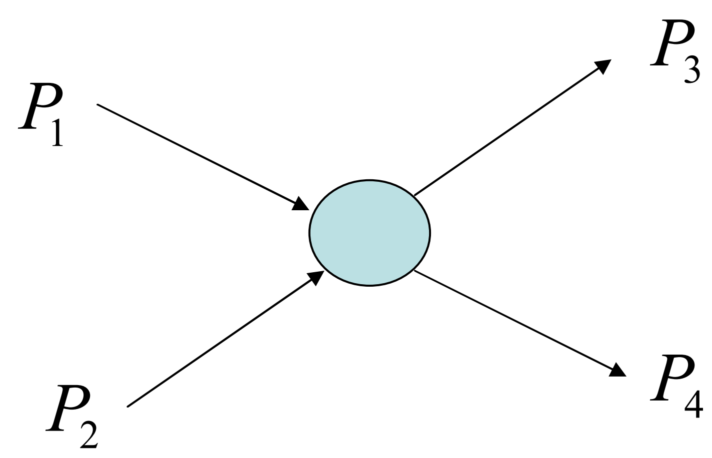
$$P^2{}_{init} = P^2{}_{thr}$$

$$2m^2{}_p + 2m_p E_{thr} = 16m^2{}_p$$

$$E_{thr} = 7m_p$$

$$T_{k,thr} = E_{thr} - m_p = 6m_p$$

Kinematika - Mandelstamovy invarianty s a t



$$s = (P_1 + P_2)^2$$

$cms:$

$$P_1 = (E_1, \overrightarrow{p^*}), P_2 = (E_2, -\overrightarrow{p^*})$$

$$s = (E_1 + E_2)^2 - (\overrightarrow{p^*} - \overrightarrow{p^*})^2 = (E_1 + E_2)^2 = E_{cms}^2 > 0$$

$$t = (P_3 - P_1)^2$$

$cms:$

$$P_1 = (E_1, \overrightarrow{p_1^*}), P_3 = (E_3, \overrightarrow{p_3^*})$$

$$t = (E_1 - E_3)^2 - (\overrightarrow{p_1^*} - \overrightarrow{p_3^*})^2 = M_1^2 + M_3^2 - 2(E_1 E_3 - \overrightarrow{p_1^*}\,\overrightarrow{p_3^*})$$

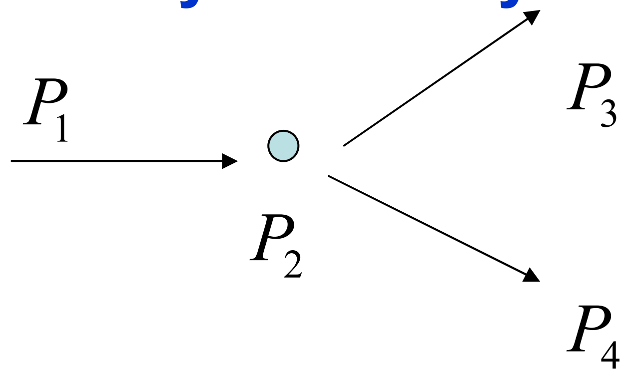
$$M_1 = M_3 = M \Rightarrow E_1 = E_3 = E;$$

$$M_1 = M_3 \;\&\; M_2 = M_4 \Rightarrow \left|\overrightarrow{p_1^*}\right| = \left|\overrightarrow{p_3^*}\right| = \left|\overrightarrow{p^*}\right|$$

$$t = 2M^2 - 2\left(E^2 - \left|\overrightarrow{p^*}\right|^2 \cos(\theta^*)\right) = -2\left(\left(E^2 - M^2\right) - \left|\overrightarrow{p^*}\right|^2 \cos(\theta^*)\right) =$$

$$-2\left|\overrightarrow{p^*}\right|^2 \left(1 - \cos(\theta_{13})\right) = -4\left|\overrightarrow{p^*}\right|^2 \sin^2(\theta^*/2) = -\left|\vec{q}\right|^2$$

Kinematika - Mandelstamovy invarianty s a t



$$t = (P_3 - P_1)^2 = (P_4 - P_2)^2$$

$lab:$

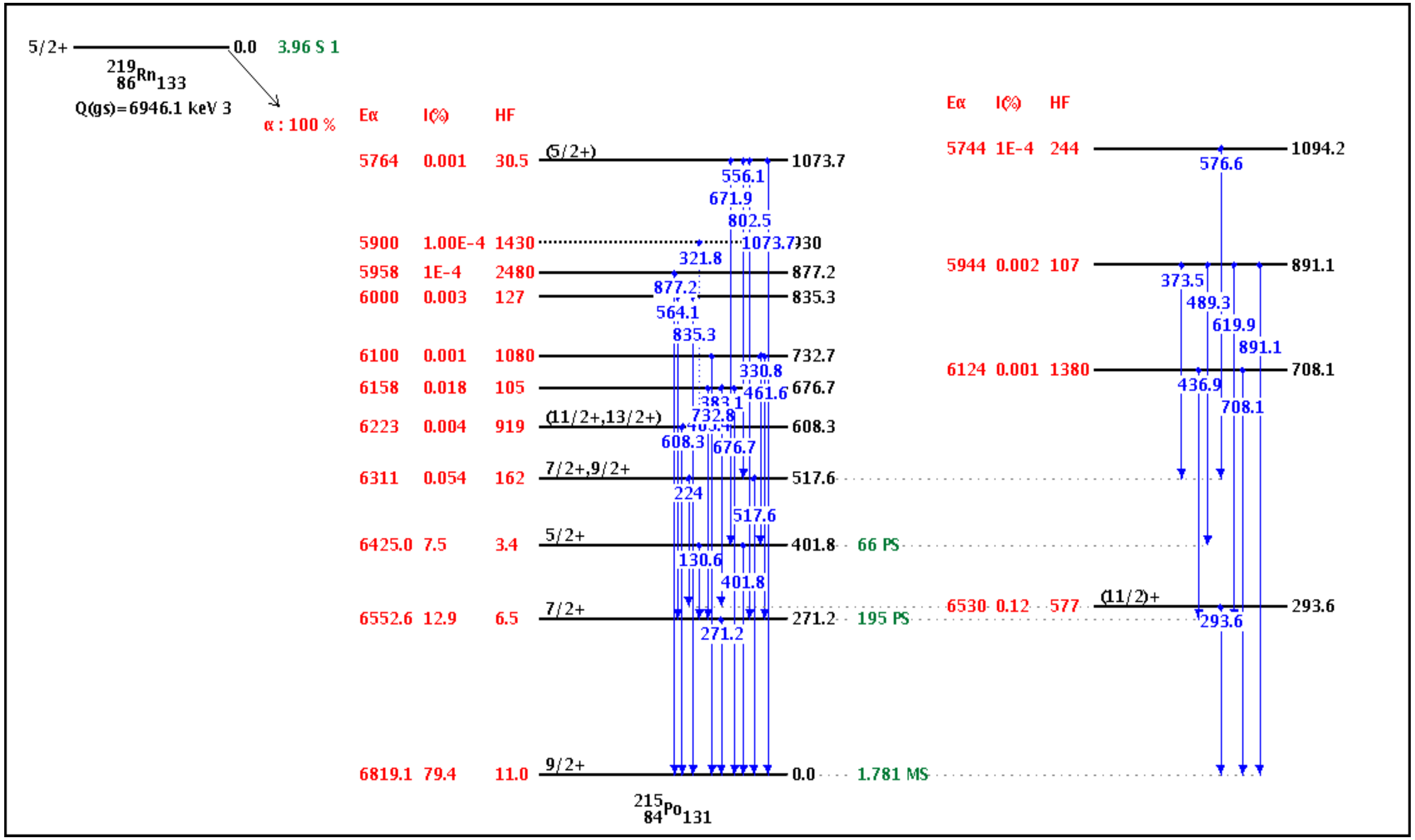
$$P_4 = (E, \vec{p}), P_2 = (m, \vec{0})$$

$$t = (E - m)^2 - (\vec{p})^2 = m^2 - 2Em + m^2 = -2m(E - m) = -2mT_k$$

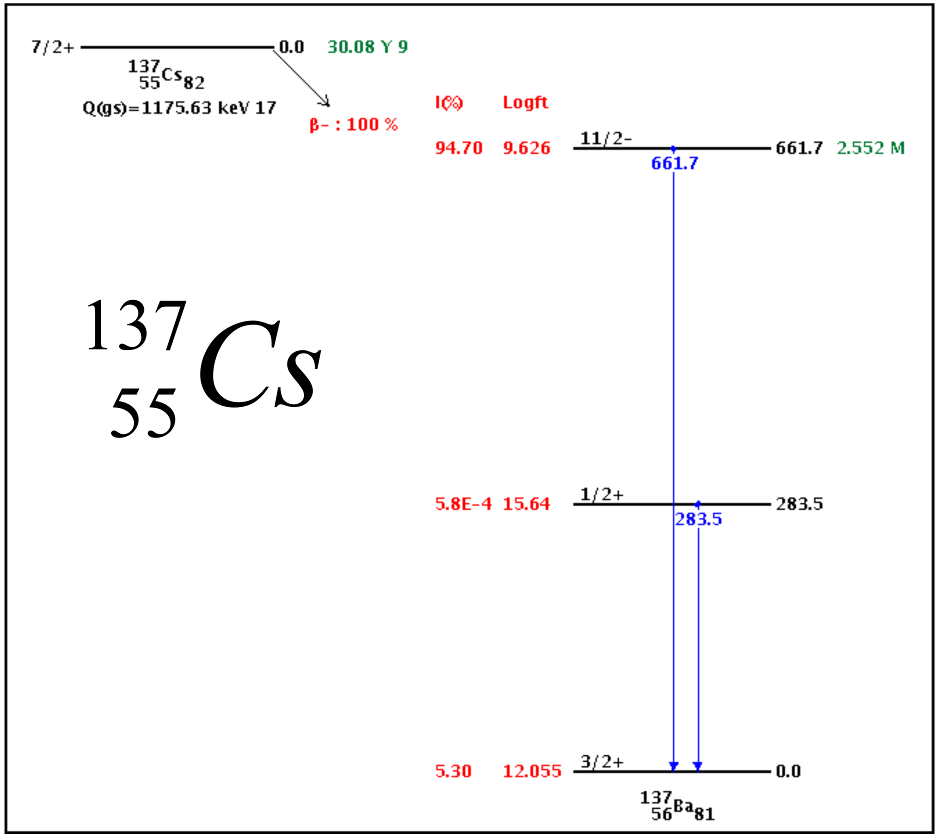
$$T_k = \frac{-t}{2m}$$

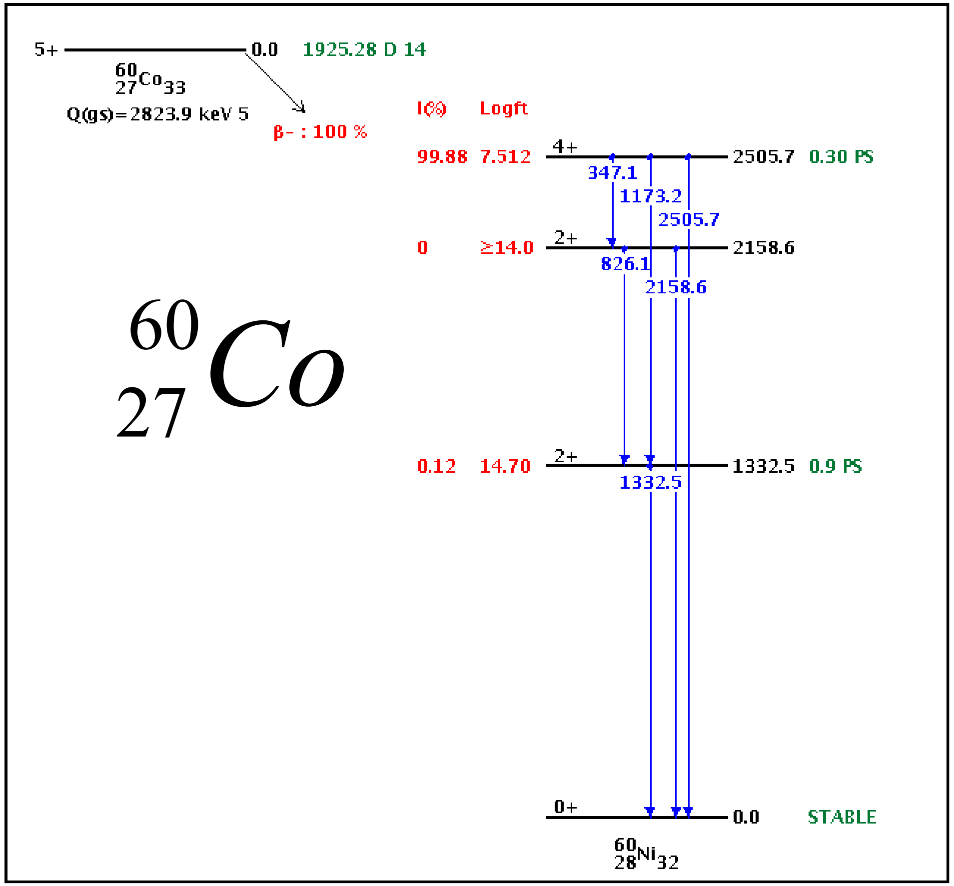
$$\left(cf : T_k = \frac{p^2}{2m} \right)$$

Vzbuzené stavy jader a gama záření



Příklady známých gama zářičů





The Nobel Prize in Physics 1961

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

"for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name"

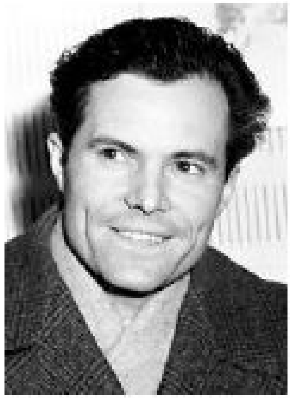
Robert Hofstadter

1/2 of the prize

USA

Stanford University
Stanford, CA, USA

b. 1915
d. 1990



Rudolf Ludwig Mössbauer

1/2 of the prize

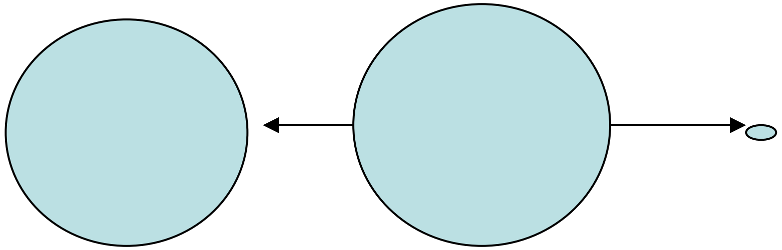
Federal Republic of Germany

Technical University Munich, Federal Republic of Germany; California Institute of Technology (Caltech)
Pasadena, CA, USA

b. 1929

Měření šířek gama přechodů a Mössbauerův jev

Při gama přechodu jádro odnáší část energie a tak je energie gama o něco menší

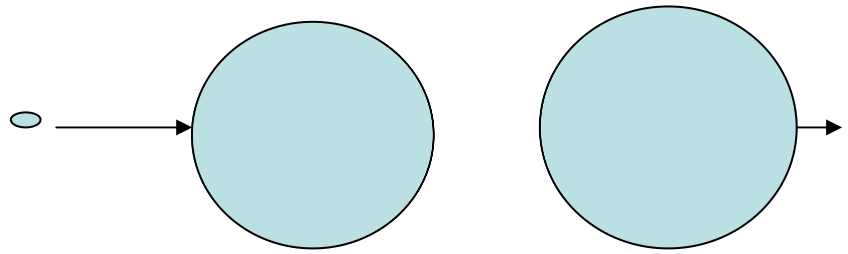


$$(M + E_\gamma) \rightarrow M \quad + \quad E'_\gamma$$

$$E'_\gamma = \frac{(M + E_\gamma)^2 - M^2}{2(M + E_\gamma)} = \frac{2ME_\gamma + E^2_\gamma}{2(M + E_\gamma)} =$$

$$\frac{2E_\gamma (M + E_\gamma) - E^2_\gamma}{2(M + E_\gamma)} = E_\gamma - \frac{E^2_\gamma}{2(M + E_\gamma)}$$

Naopak pro vybuzení jádra do excitovaného stavu je třeba energie o něco málo větší než odpovídá energii gama přechodu

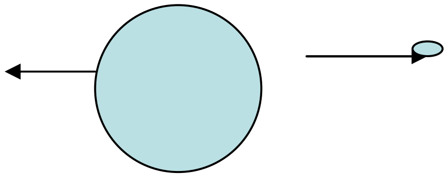


$$E''_\gamma \quad + \quad M \rightarrow (M + E_\gamma)$$

$$(E''_\gamma + M)^2 - \left(E''_\gamma\right)^2 = (M + E_\gamma)^2$$

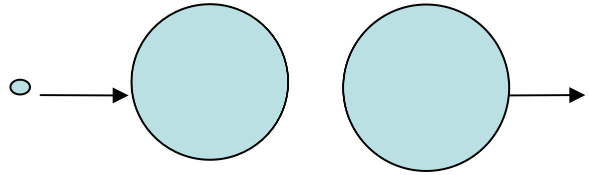
$$2E''_\gamma M = 2E_\gamma M + E^2_\gamma$$

$$E''_\gamma = E_\gamma + \frac{E^2_\gamma}{2M}$$



$$(M+E_\gamma)\rightarrow M \quad + \quad E'_\gamma$$

$$E'_\gamma = E_\gamma - \frac{E^2_\gamma}{2(M+E_\gamma)}$$



$$E''_\gamma \quad + \quad M \rightarrow (M+E_\gamma)$$

$$E''_\gamma = E_\gamma + \frac{E^2_\gamma}{2M}$$

$$({}^{191}_{77}Ir + 129keV) \rightarrow \quad + \quad E'_\gamma$$

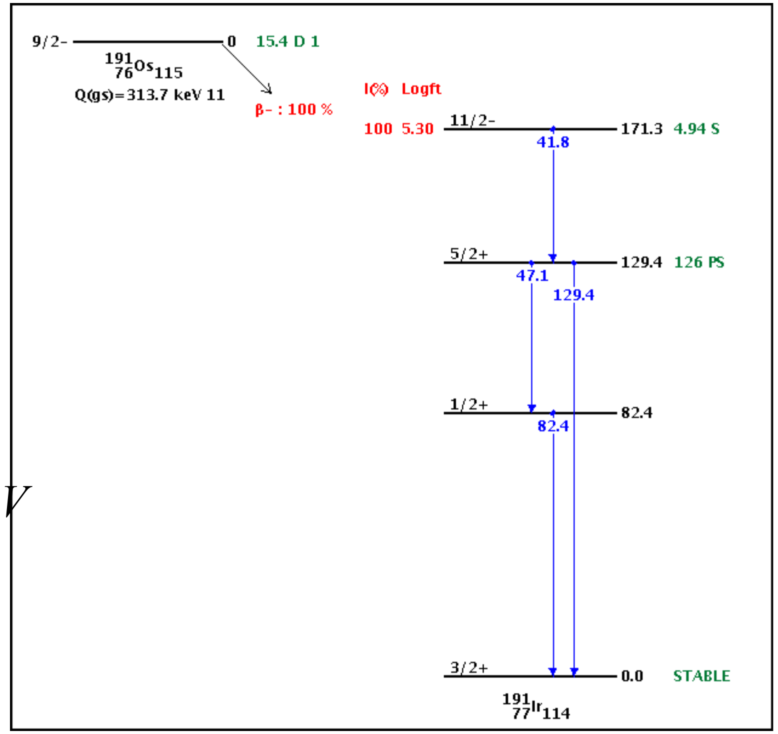
$$M_{{}^{191}_{77}Ir} = (77\cdot 938{,}27 + (191-77)\cdot 939{,}57 - 191\cdot 8{,}5)MeV =$$

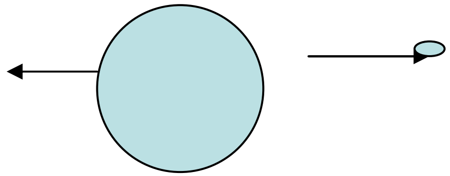
$$177734MeV$$

$$E'_\gamma - 129keV = -\frac{\left(129\cdot 10^3\right)^2 eV^2}{2\cdot 177734\cdot 10^6 eV} = 46{,}8\cdot 10^{-3} eV$$

$$E''_\gamma - 129keV = \frac{\left(129\cdot 10^3\right)^2 eV^2}{2\cdot(177734\cdot 10^6 + 129\cdot 10^3)eV} = 46{,}8\cdot 10^{-3} eV$$

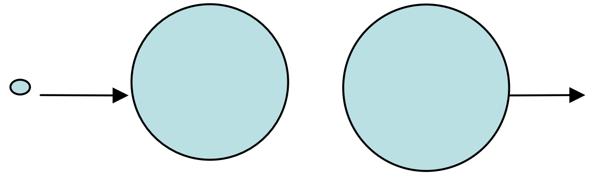
$$\Gamma = \frac{\hbar c}{c\tau} = \frac{\hbar c}{c(T_{1/2}/\ln(2))} = \frac{197\cdot 10^6 eV 10^{-13} cm}{30cm/ns\cdot 0{,}126ns/0{,}69} = 3{,}6\cdot 10^{-6} eV$$





$$(M+E_\gamma) \rightarrow M \quad + \quad E'_\gamma$$

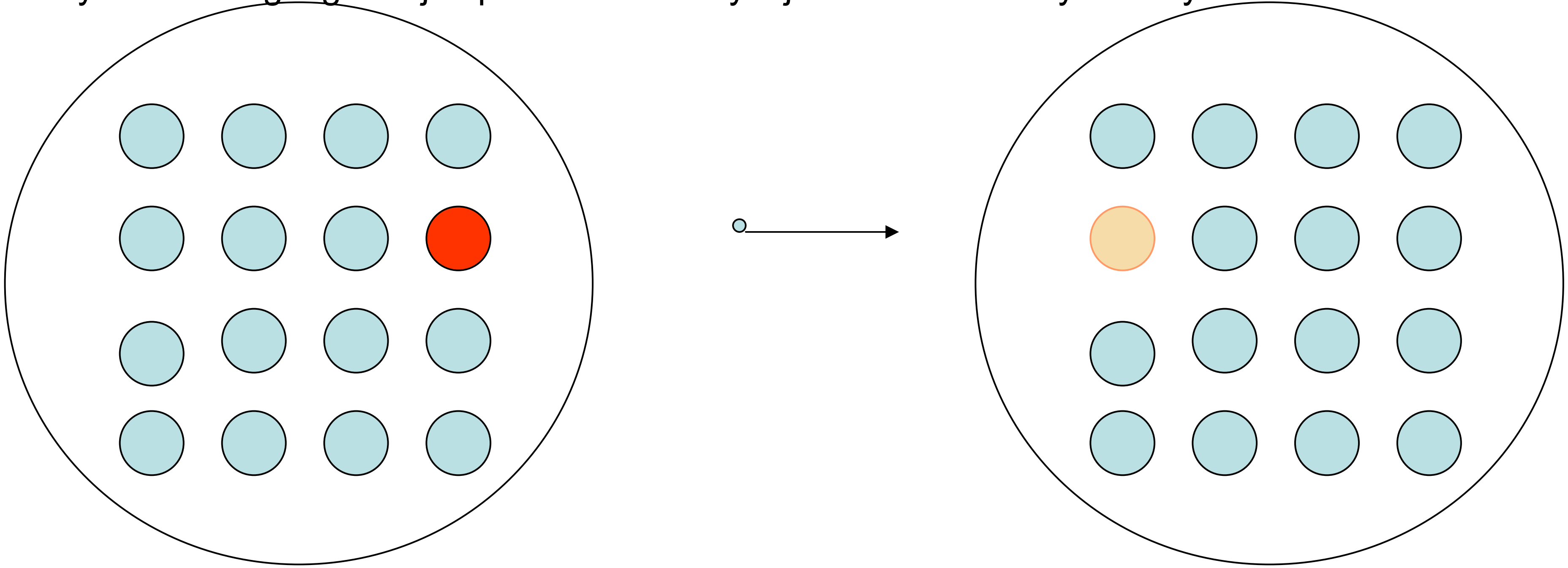
$$E'_\gamma = E_\gamma - \frac{E^2_\gamma}{2(M+E_\gamma)}$$



$$E''_\gamma \quad + \quad M \rightarrow (M+E_\gamma)$$

$$E''_\gamma = E_\gamma + \frac{E^2_\gamma}{2M}$$

Je-li atom zabudován do krystalu (M→M krystal), pak při nízké teplotě je odražen celý krystal a energie gama je správná na to aby v jiném takovém krystalu byla absorbována



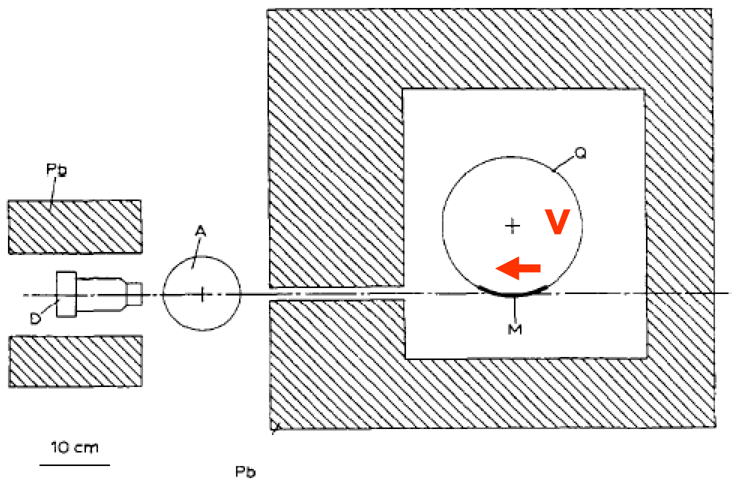


Fig. 7. Experimental arrangement. A, absorber-cryostat; Q, rotating cryostat with source; D, scintillation detector.

$$({}^{191}_{77}Ir + 129keV) \rightarrow \; {}^{191}_{77}Ir + \; E'_{\gamma}$$

$$\Gamma = 3{,}6 \cdot 10^{-6} eV$$

$$129 \cdot 10^{3} \beta eV = 3{,}6 \cdot 10^{-6} eV$$

$$\beta = \frac{3{,}6 \cdot 10^{-6} eV}{129 \cdot 10^{3} eV} = 2{,}8 \cdot 10^{-11}$$

$$v = 2{,}8 \cdot 10^{-11} \cdot 3 \cdot 10^{10} cm/s = 0{,}84 cm/s$$

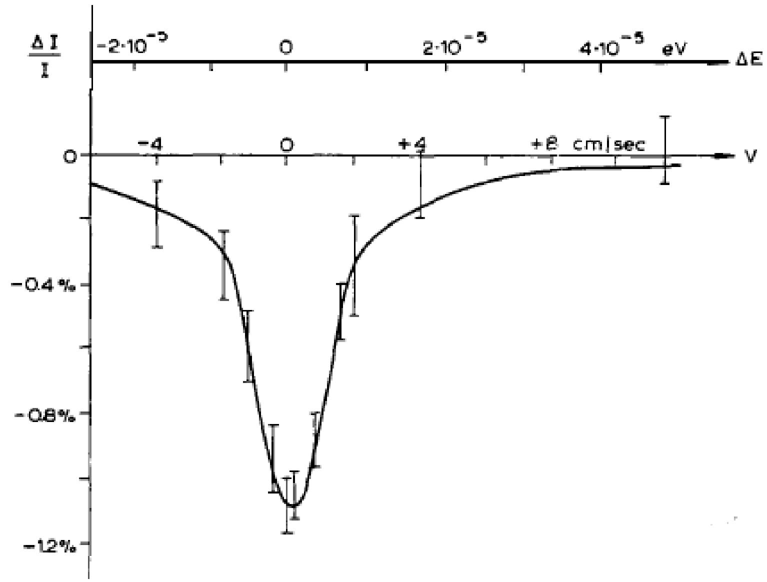


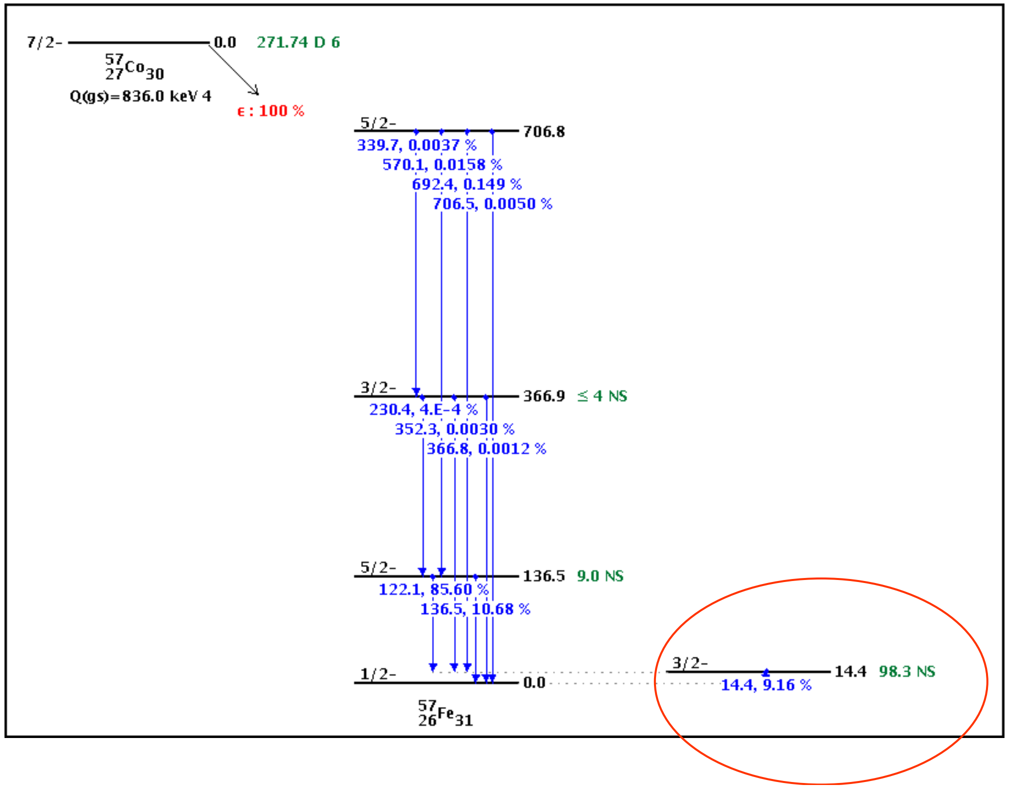
Fig. 8. Relative intensity ratio $\Delta I/I$ of gamma radiation measured behind the resonant iridium absorber, in comparison with intensities measured behind a nonresonant absorber.

$^{57}_{26}Fe$

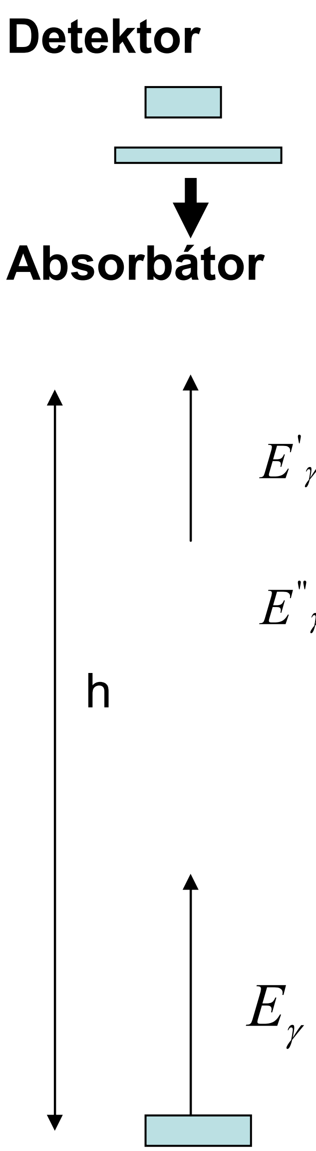
$$M_{^{57}_{26}Fe} = (26\cdot 938{,}27 + (57-26)\cdot 939{,}57 - 57\cdot 8{,}8)MeV =$$

$$53020 MeV$$

$$\Gamma = \frac{\hbar c}{c\tau} = \frac{\hbar c}{c(T_{1/2}/\ln(2))} = \frac{197\cdot 10^{6} eV 10^{-13} cm}{30 cm/ns \cdot 98{,}3 ns/0{,}69} = 46\cdot 10^{-10} eV$$



Prověrka obecné teorie relativity



Rezonanční absorbce 14,4 keV gama. Rudý posuv gama je kompenzován pohybem absorbátoru. Experiment Repky

$$E'_\gamma = E_\gamma - \frac{E_\gamma}{c^2} gh$$

$$E''_\gamma = \gamma(E'_\gamma + \beta E'_\gamma) = \frac{1}{\sqrt{1-\beta^2}}(E'_\gamma + \beta E'_\gamma) \cong (1+\frac{\beta^2}{2})(E'_\gamma + \beta E'_\gamma) \cong E'_\gamma(1+\beta)$$

$$E_\gamma(1-\frac{gh}{c^2})(1+\beta)\frac{1}{\sqrt{1-\beta^2}} \cong E_\gamma(1-\frac{gh}{c^2})(1+\beta) \cong E_\gamma(1-\frac{gh}{c^2}+\beta) = E_\gamma$$

$$\beta = \frac{gh}{c^2} = \frac{10m/s^2 \cdot 20m}{9 \cdot 10^{16} m^2/s^2} = 2{,}2 \cdot 10^{-15} \Rightarrow v = 2{,}2 \cdot 10^{-15} \cdot 3 \cdot 10^8 m/s =$$

$$6{,}6 \cdot 10^{-4} mm/s = 0{,}66 \mu m/s$$

Interakce jaderného záření s prostředím

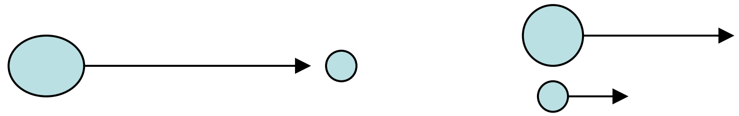
Ionizace – nabité částice
Brzdné záření – elektrony
Interakce gama záření

Ionizační ztráty

- týkají se všech nabitých částic

Tmax

$$\left(E,\vec{P}\right) \quad + \quad (m_e,\vec{0}) \quad = \quad \left(E',\vec{P'}\right)+\left(E_e,\vec{p_e}\right)$$



$$E+m_e=E'+E_e \quad ; \quad \vec{P}=\vec{P'}+\vec{p_e}$$

$$E'=E+m_e-E_e \quad ; \quad \left|\vec{P'}\right|=\left|\vec{P}\right|-\left|\vec{p_e}\right|$$

$$M^2=E'^2-\left|\vec{P'}\right|^2=\left(E+m_e-E_e\right)^2-\left(\left|\vec{P}\right|-\left|\vec{p_e}\right|\right)^2$$

$$M^2=\left(E^2-\left|\vec{P}\right|^2\right)+\left(E_e{}^2-\left|\vec{p_e}\right|^2\right)+m_e{}^2+2Em_e-2EE_e-2m_eE_e+2\left|\vec{P}\right|\left|\vec{p_e}\right|$$

$$0=2m_e{}^2+2Em_e-2EE_e-2m_eE_e+2\left|\vec{P}\right|\left|\vec{p_e}\right|$$

$$\left(\left|\vec{P}\right|\left|\vec{p_e}\right|\right)^2=(E_e-m_e)^2(E+m_e)^2$$

$$\left|\vec{P}\right|^2(E_e{}^2-m_e{}^2)=\left|\vec{P}\right|^2(E_e-m_e)(E+m_e)=(E_e-m_e)^2(E+m_e)^2$$

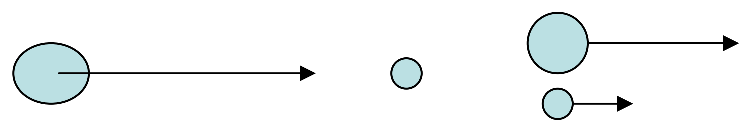
$$\left|\vec{P}\right|^2(\tau_{k,\max}+2m_e)=(E+m_e)^2\tau_{k,\max} \quad ; \quad \tau_{k,\max}((E+m_e)^2-\left|\vec{P}\right|^2)=\left|\vec{P}\right|^2 2m_e$$

$$\tau_{k,\max}=\frac{2m_e\left|\vec{P}\right|^2}{M^2+2Em_e+m_e{}^2}=\frac{2m_e\left|\vec{P}\right|^2/M^2}{1+2(E/M)(m_e/M)+(m_e/M)^2}$$

$$\tau_{k,\max}=\frac{2m_e\beta^2\gamma^2}{1+2\gamma\frac{m_e}{M}+\left(\frac{m_e}{M}\right)^2}$$

Tmax

$$\tau_{k,\max} = \frac{2m_e\beta^2\gamma^2}{1+2\gamma\frac{m_e}{M}+\left(\frac{m_e}{M}\right)^2}$$



Tmin

Ionizační ztráty - týkají se všech nabitých částic

$$\frac{\pi(r^2{}_{\min}/8)}{\sin^4(\theta/2)} = \frac{d\sigma}{d\cos(\theta)} = \frac{d\sigma}{d(1-\cos(\theta))} = \frac{2P^2 d\sigma}{d\left(4P^2(1-\cos(\theta))/2\right)} = \frac{2P^2 d\sigma}{d(4P^2\sin^2(\theta/2))} = \frac{2P^2 d\sigma}{dq^2}$$

$$\frac{2P^2 d\sigma}{dq^2} = \frac{\pi(r^2{}_{\min}/8)}{\sin^4(\theta/2)} = \frac{(2P)^4\pi(r^2{}_{\min}/8)}{(2P)^4\sin^4(\theta/2)} = \frac{(2P)^4\pi(r^2{}_{\min}/8)}{q^4}$$

$$\frac{d\sigma}{dq^2} = \frac{P^2\pi r^2{}_{\min}}{q^4} \Rightarrow \frac{d\sigma}{d|t|} = \frac{P^2\pi r^2{}_{\min}}{|t|^2}$$

$$\frac{d\sigma}{2m_e d\frac{|t|}{2m_e}} = \frac{P^2\pi r^2{}_{\min}}{4m^2{}_e\left(\frac{|t|}{2m_e}\right)^2}$$

$$r_e = \frac{\alpha(\hbar c)}{m_e}$$

$$\frac{d\sigma}{d\tau_k} = \frac{P^2\pi r^2{}_{\min}}{2m_e}\frac{1}{\tau^2{}_k} = \frac{m_e P^2\pi\alpha^2(\hbar c)^2}{2m_e{}^2 T_k^2}\frac{1}{\tau^2{}_k} = \frac{P^2}{2T_k^2} m_e\pi r_e^2\frac{1}{\tau^2{}_k} =$$

$$\frac{(\gamma\beta)^2 M^2}{2(\gamma-1)^2 M^2} m_e\pi r_e^2\frac{1}{\tau^2{}_k} = \frac{\gamma^2-1}{2(\gamma-1)^2} m_e\pi r_e^2\frac{1}{\tau^2{}_k} = \frac{\gamma+1}{2(\gamma-1)} m_e\pi r_e^2\frac{1}{\tau^2{}_k} =$$

$$\frac{(\gamma+1)^2}{2(\gamma^2-1)} m_e\pi r_e^2\frac{1}{\tau^2{}_k} = \frac{(\gamma+1)^2}{2(\gamma\beta)^2} m_e\pi r_e^2\frac{1}{\tau^2{}_k} = 2\left(\frac{\gamma+1}{2}\right)^2\frac{1}{(\gamma\beta)^2} m_e\pi r_e^2\frac{1}{\tau^2{}_k}$$

$$\frac{d\sigma}{d\tau_k} = 2\left(\frac{\gamma+1}{2}\right)^2 \frac{1}{(\gamma\beta)^2} m_e \pi r_e^2 \frac{1}{\tau^2{}_k}$$

$$p = \sigma \cdot \Delta x \cdot \rho \cdot \frac{N_A}{A} Z$$

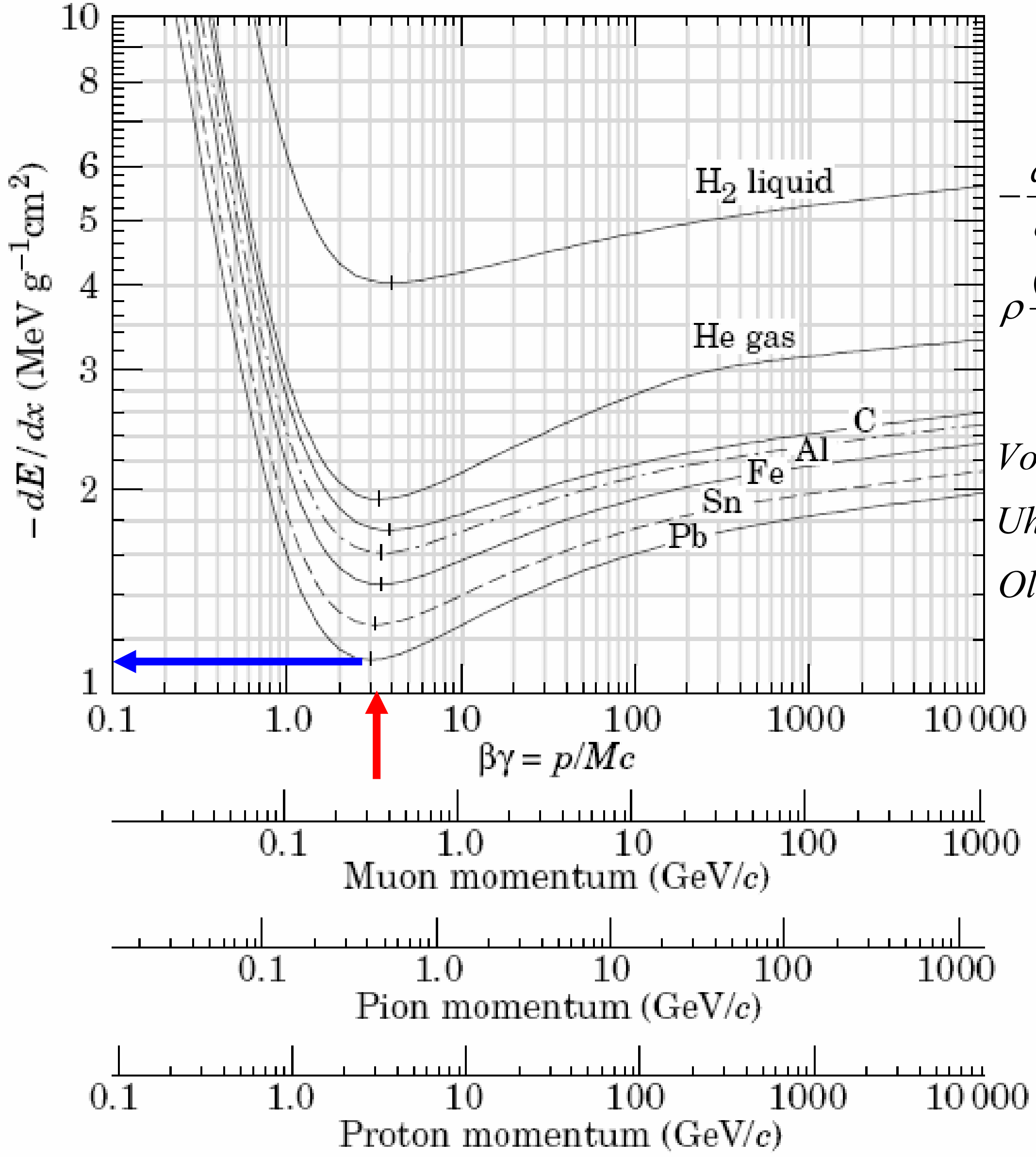
$$\frac{dp}{d\tau_k} = \Delta x \cdot \rho \cdot \frac{N_A}{A} Z \cdot 2\left(\frac{\gamma+1}{2}\right)^2 \frac{1}{(\gamma\beta)^2} m_e \pi r_e^2 \frac{1}{\tau^2{}_k}$$

$$\langle \tau_k \rangle = \int_{\tau_{\min}}^{\tau_{\max}} \tau_k \frac{dp}{d\tau_k} d\tau_k = \Delta x \cdot \rho \cdot \frac{N_A}{A} Z \cdot 2\left(\frac{\gamma+1}{2}\right)^2 \frac{1}{(\gamma\beta)^2} m_e \pi r_e^2 \int_{\tau_{\min}}^{\tau_{\max}} \tau_k \frac{1}{\tau_k} d\tau_k =$$

$$\Delta x \cdot \rho \cdot \frac{N_A}{A} Z \cdot 2\left(\frac{\gamma+1}{2}\right)^2 \frac{1}{(\gamma\beta)^2} m_e \pi r_e^2 \ln\left(\frac{\tau_{\max}}{\tau_{\min}}\right)$$

$$\boxed{-\frac{\Delta T_k}{\Delta x} = \rho \cdot \frac{N_A}{A} Z \cdot 2\left(\frac{\gamma+1}{2}\right)^2 \frac{1}{(\gamma\beta)^2} m_e \pi r_e^2 \ln\left(\frac{\tau_{\max}}{\tau_{\min}}\right)}$$

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



$$-\frac{dE}{dx}[MeV/cm] = \rho[gcm^{-3}]\cdot 4[MeV/(gcm^{-2})]\frac{Z}{A}\frac{1}{\beta^2} =$$

$$\rho\frac{(dE/dx)_{\min}}{\beta^2}$$

$Vodík: (dE/dx)_{\min} = 4MeV/(gcm^{-2})$

$Uhlík, voda: (dE/dx)_{\min} = 2MeV/(gcm^{-2})$

$Olovo: (dE/dx)_{\min} = 1{,}12MeV/(gcm^{-2})$

Doběh :

$$-\frac{dE}{dx}=\frac{(dE/dx)_{\min}\cdot\rho}{\beta^2}=\frac{(dE/dx)_{\min}\cdot\rho}{(E^2-m^2)/E^2}$$

$$-dE\,\frac{E^2-m^2}{E^2}=(dE/dx)_{\min}\cdot\rho\cdot dx$$

$$-\int_{E_o}^{m}dE\left(1-\frac{m^2}{E^2}\right)=(dE/dx)_{\min}\cdot\rho\int_0^R dx$$

$$-(m-E_0)-m^2\left(\frac{1}{m}-\frac{1}{E_0}\right)=(dE/dx)_{\min}\cdot\rho\cdot R$$

$$E_0-2m+\frac{m^2}{E_0}=(dE/dx)_{\min}\cdot\rho\cdot R$$

$$\boxed{R}=\frac{E_0-m}{(dE/dx)_{\min}\cdot\rho}\frac{E_0-m}{E_0}=\boxed{\frac{T_k}{(dE/dx)_{\min}\cdot\rho}\frac{T_k}{T_k+m}}$$

$T_k << m:$

$$R=\frac{T_k}{(dE/dx)_{\min}/\rho}\frac{T_k}{m}\approx T_k^{\ 2}$$

$T_k >> m:$

$$R=\frac{T_k}{(dE/dx)_{\min}/\rho}\approx T_k$$

$Př.:$

$$\alpha, m = \left(2\cdot 938{,}27 + 2\cdot 939{,}57 - 28\right) MeV = 3725{,}68\, MeV$$

$$T_k = 7{,}7\, MeV$$

$vzduch:$

$$\left(dE/dx\right)_{\min} = 2{,}0\, MeV/(g\cdot cm^{-2})$$

$$\rho = 0{,}0012\, g\cdot cm^{-3}$$

$$R = \frac{T_k}{\left(dE/dx\right)_{\min}\cdot\rho}\frac{T_k}{T_k+m} = \frac{7{,}7\,MeV}{2{,}0\,\dfrac{MeV}{g\cdot cm^{-2}}\cdot 0{,}0012\, g\cdot cm^{-3}}\frac{7{,}7\,MeV}{(7{,}7+3725{,}68)\,MeV} = 6{,}62\, cm$$

$voda:$

$$\left(dE/dx\right)_{\min} = 2{,}0\, MeV/(g\cdot cm^{-2})$$

$$\rho = 1{,}0\, g\cdot cm^{-3}$$

$$R = \frac{T_k}{\left(dE/dx\right)_{\min}\cdot\rho}\frac{T_k}{T_k+m} = \frac{7{,}7\,MeV}{2{,}0\,\dfrac{MeV}{g\cdot cm^{-2}}\cdot 1{,}0\, g\cdot cm^{-3}}\frac{7{,}7\,MeV}{(7{,}7+3725{,}68)\,MeV} = 7{,}9\cdot 10^{-3}\, cm = 79\,\mu m$$

$zlato:$

$$\left(dE/dx\right)_{\min} = 1{,}13\, MeV/(g\cdot cm^{-2})$$

$$\rho = 20\, g\cdot cm^{-3}$$

$$R = \frac{T_k}{\left(dE/dx\right)_{\min}\cdot\rho}\frac{T_k}{T_k+m} = \frac{7{,}7\,MeV}{1{,}13\,\dfrac{MeV}{g\cdot cm^{-2}}\cdot 20{,}0\, g\cdot cm^{-3}}\frac{7{,}7\,MeV}{(7{,}7+3725{,}68)\,MeV} = 7{,}0\cdot 10^{-4}\, cm = 7\,\mu m$$

Interakce elektronů:

Jakož i jiné nabité částice ionizují,

$$T_{k,\max} = \frac{2m_e\beta^2\gamma^2}{1+2\gamma\frac{m_e}{M}+\left(\frac{m_e}{M}\right)^2}$$

$$M = m_e$$

$$T_{k,\max} = \frac{2m_e\beta^2\gamma^2}{1+2\gamma+1} = \frac{2m_e\beta^2\gamma^2}{2(1+\gamma)} = \frac{m_e(\gamma^2-1)}{(1+\gamma)} = m_e(\gamma-1) = T_k$$

Při energiích E> 20 MeV dominuje brzdné záření – bremsstrahlung

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

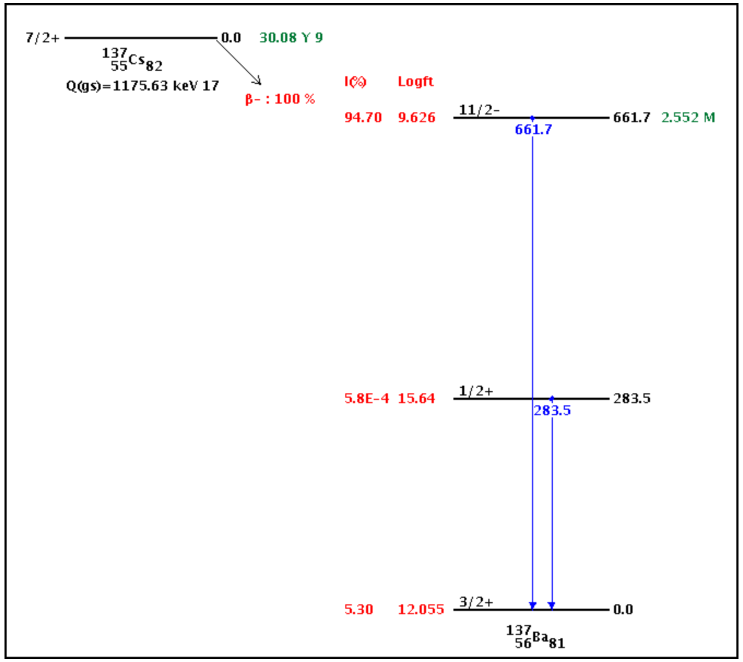
$$E = E_0 e^{-L/X_0}$$

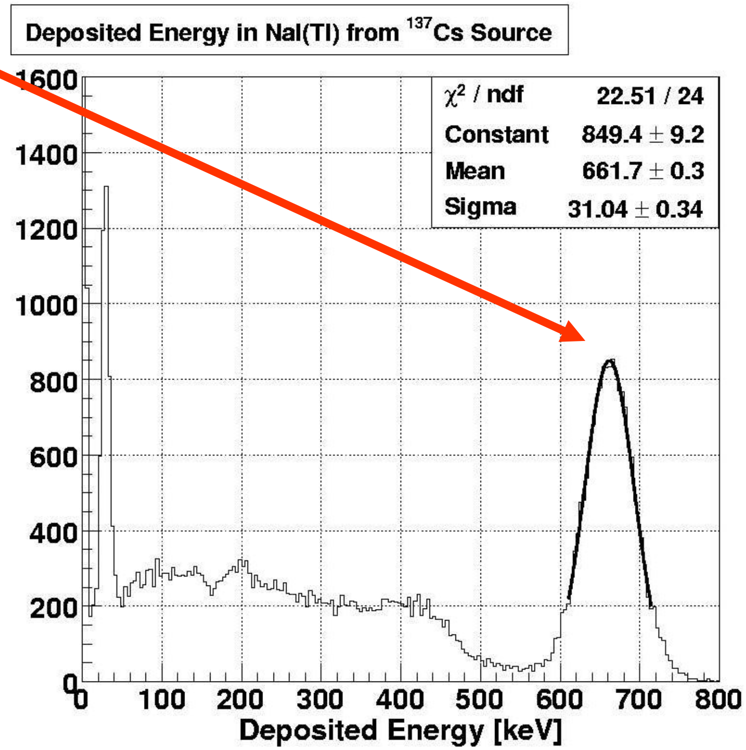
$$X_0(vzduch) = 304m; X_0(voda) = 36cm$$

$$X_0(Fe) = 1{,}8cm; X_0(Pb) = 5{,}6mm$$

Interakce záření gama

Fotoefekt, Comptonův rozptyl, Tvorba párů elektron-positron





Compton :

$$E_\gamma + m_e = E'_\gamma + \sqrt{m_e^2 + p_e^2} \Rightarrow p_e^2 = \left(E_\gamma - E'_\gamma + m_e\right)^2 - m_e^2$$

$$E_\gamma = E'_\gamma \cos(\theta) + p_e \cos(\phi)$$

$$E'_\gamma \sin(\theta) = p_e \sin(\phi)$$

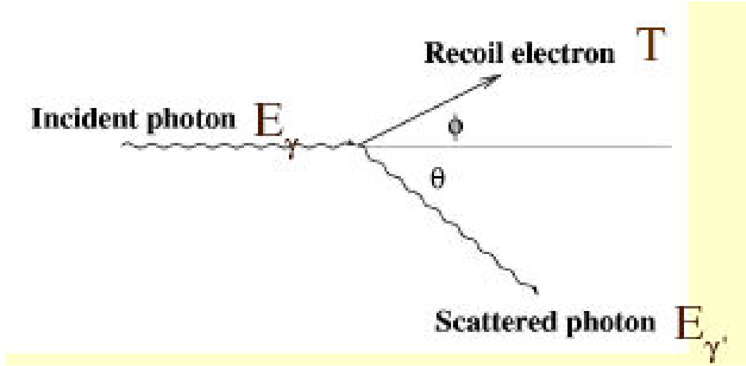
$$\Rightarrow p_e^2 = \left(E_\gamma - E'_\gamma \cos(\theta_\gamma)\right)^2 + \left(E'_\gamma \sin(\theta_\gamma)\right)^2$$

$$\left(E_\gamma - E'_\gamma \cos(\theta)\right)^2 + \left(E'_\gamma \sin(\theta)\right)^2 = \left(E_\gamma - E'_\gamma + m_e\right)^2 - m_e^2$$

$$E^2_\gamma - 2E_\gamma E'_\gamma \cos(\theta) + E'^2_\gamma = E^2_\gamma + E'^2_\gamma - 2E_\gamma E'_\gamma + 2m_e E_\gamma - 2E_\gamma m_e$$

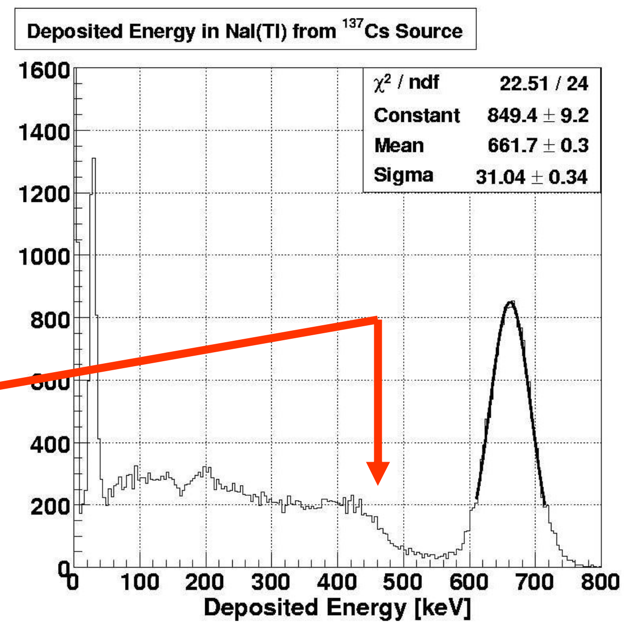
$$E'_\gamma\left(E_\gamma(1-\cos(\theta)) + m_e\right) = m_e E_\gamma$$

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e}(1-\cos(\theta))}$$



$$\Delta E_\gamma = E_\gamma - E'_\gamma = E_\gamma - \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e}(1-\cos(\theta))} = \frac{\frac{E_\gamma}{m_e}(1-\cos(\theta))}{1 + \frac{E_\gamma}{m_e}(1-\cos(\theta))} E_\gamma$$

$$\Rightarrow \Delta E_{\gamma\,\max} = E_\gamma \frac{2\frac{E_\gamma}{m_e}}{1 + 2\frac{E_\gamma}{m_e}} = \frac{2E^2_\gamma}{m_e + 2E_\gamma}$$



Tvorba elektron-positronových párů

$$\gamma + M \rightarrow M + e^{+} + e^{-}$$

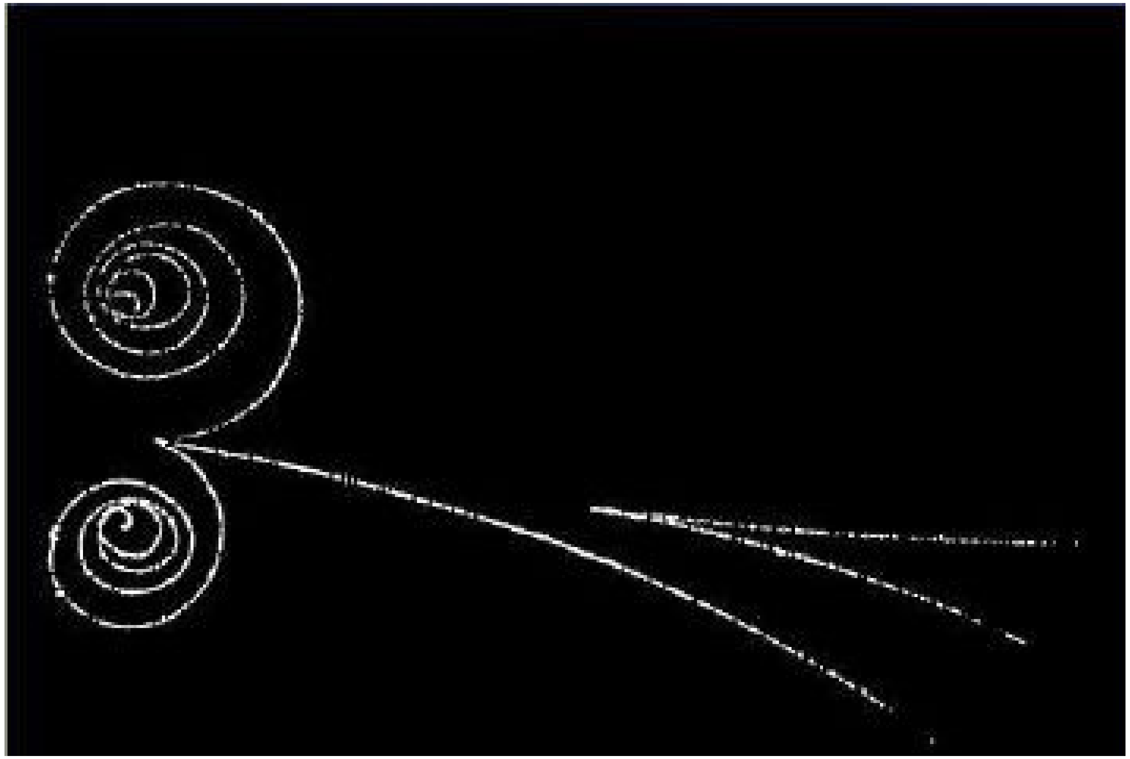
Prahová energie gama:

$$\left(E^{thr}{}_{\gamma} + M\right)^{2} - E^{thr\,2}{}_{\gamma} = (M + 2m_{e})^{2}$$

$$2E^{thr}{}_{\gamma}M = 4m_{e}M + 4m_{e}^{2}$$

$$E^{thr}{}_{\gamma} = 2m_{e}\left(1 + \frac{m_{e}}{M}\right)$$

$$\boxed{\gamma + e^{-} \rightarrow e^{-} + e^{-} + e^{+}}$$



$$M >> m_{e} \Rightarrow E^{thr}{}_{\gamma} \cong 2m_{e}$$

$$M = m_{e} \Rightarrow E^{thr}{}_{\gamma} = 4m_{e}$$

$$P(x) = 1 - e^{-\left(\sigma_{fotoefekt} + \sigma_{Compton} + \sigma_{pairs}\right) x \frac{N_A}{A} \rho}$$

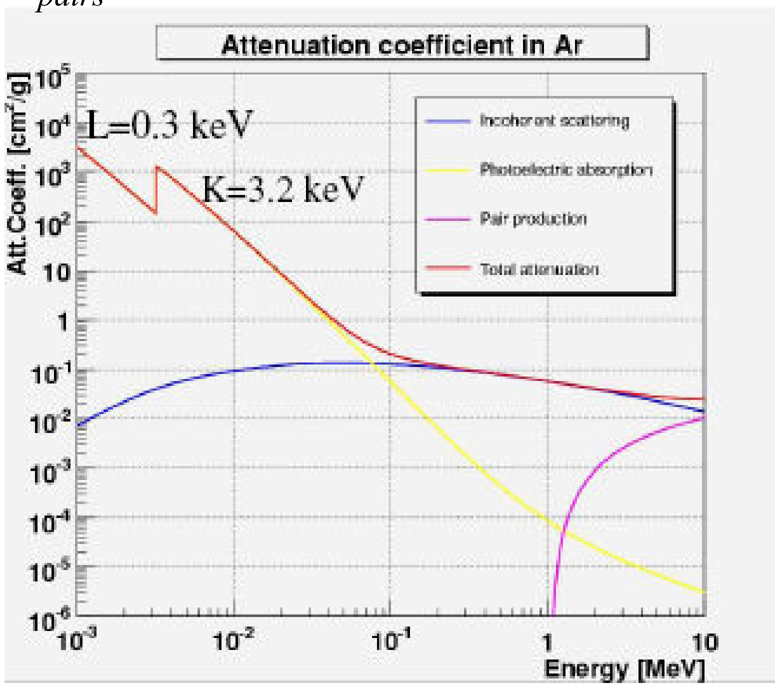
$$I(x) = I_0(1 - P(x)) = I_0 e^{-\left(\sigma_{fotoefekt} + \sigma_{Compton} + \sigma_{pairs}\right) \frac{N_A}{A} \rho x} = I_0 e^{-\mu \rho x}$$

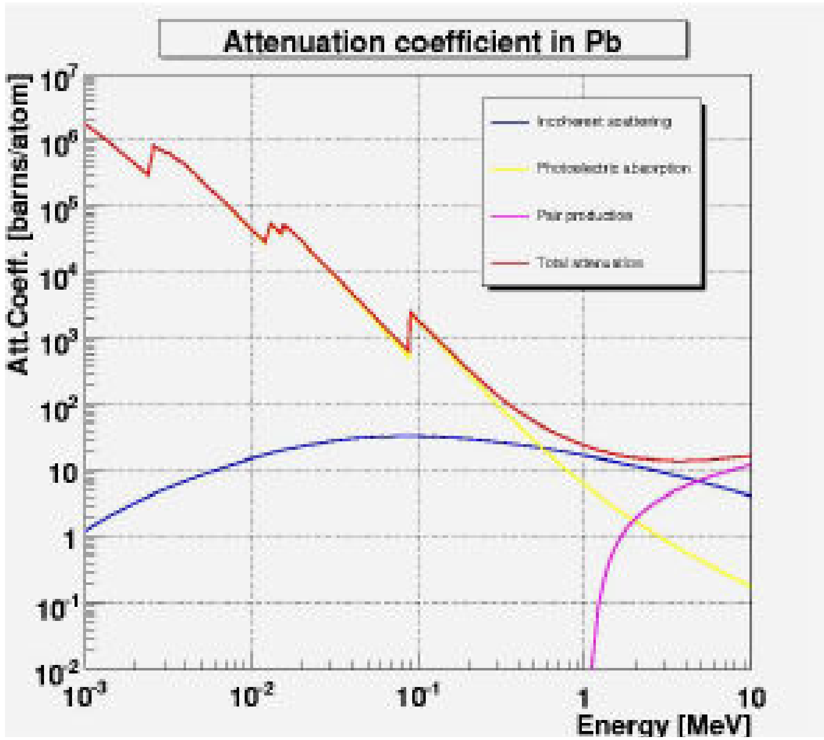
$$\mu = \left(\sigma_{fotoefekt} + \sigma_{Compton} + \sigma_{pairs}\right) \frac{N_A}{A}$$

$$\sigma_{fotoefekt} \cong Z^{(4-5)}$$

$$\sigma_{Compton} \cong Z$$

$$\sigma_{pairs} \cong Z^2$$





Radiace, jednotky

Aktivita se měří v Becquerel Bq = 1 rozpad/s

Dávka Gray G = 1 J/kg

Sievert Sv= Gray x Quality factor – určuje jak je dané záření nebezpečné pro člověka. Nejméně nebezpečné jsou miony, gama, beta (Q=1), nejvíce alfa a ostatní těžké ionty (Q=20) a neutrony s malou energií (Q~5).
Povoleno je 50mSv za rok a 100 mSv za pět let.

1MBq kobaltového gama zářiče:

$$-\Delta N = N\frac{\Delta t}{T_{1/2}/\ln(2)}$$

$$-\Delta N/\Delta t = A = \frac{N}{T_{1/2}/\ln(2)}$$

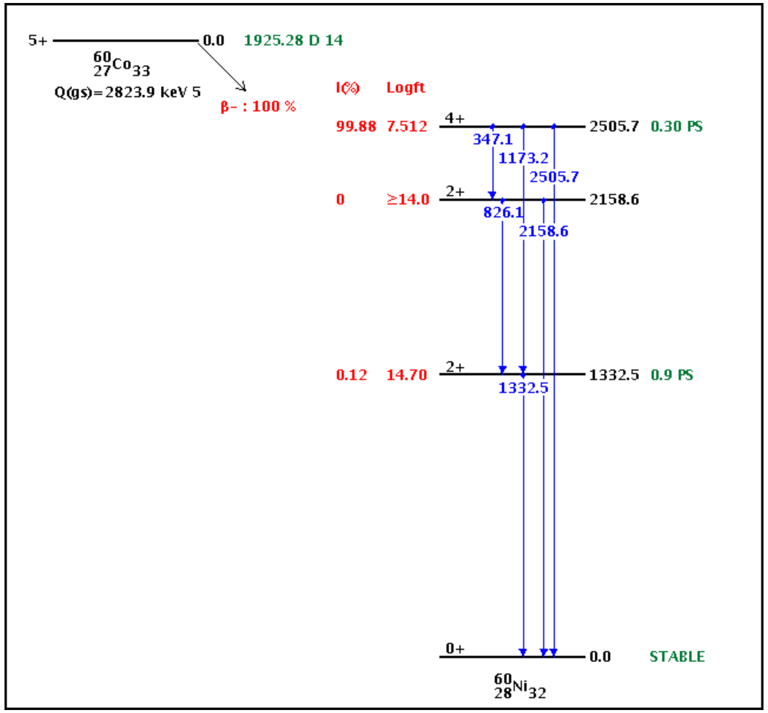
$$N = A[Bq = s^{-1}]\cdot T_{1/2}[s]/\ln(2)$$

$$A = 1MBq; T_{1/2} = 1925 days$$

$$N = 10^6 s^{-1} 1925\cdot 86400 s/0{,}69 = 0{,}24\cdot 10^{15}\ {}^{60}_{27}Co$$

$$60 g Co = 6{,}023\cdot 10^{23}\, atoms$$

$$0{,}24\cdot 10^{15}\ {}^{60}_{27}Co \Rightarrow 0{,}24\cdot 10^{15}\cdot 60 g/6{,}023\cdot 10^{23} = 2{,}4\cdot 10^{-8} g = 24 ng!!$$



Dávky záření:

Miony z kosmického záření:

$$(dE/dx)_{\min} = 2MeV/g\cdot cm^{-2} \Rightarrow \rho = 1g/cm^3; (dE/dx)_{\min} = 2MeV/cm$$

$$50cm$$

$$1mion/s/dm^2 \Rightarrow 6mion/s$$

$$DE = 2MeV/cm\cdot 50cm\cdot 6mion/s\cdot 31{,}4\cdot 10^7 s/year = 1{,}88\cdot 10^{11} MeV/year =$$

$$1{,}88\cdot 10^{11}\cdot 10^6\cdot 1{,}6\cdot 10^{-19} J/year = 3\cdot 10^{-2} J/year$$

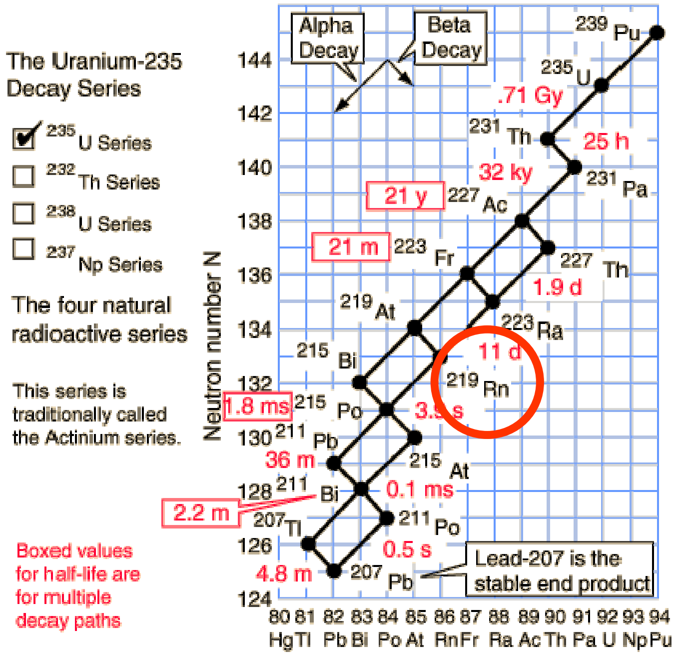
$$D = 3\cdot 10^{-2} J/year/80kg = 0{,}375mJ/year = \underline{0{,}375mSv/rok}$$

V Troji ve vstupní hale:

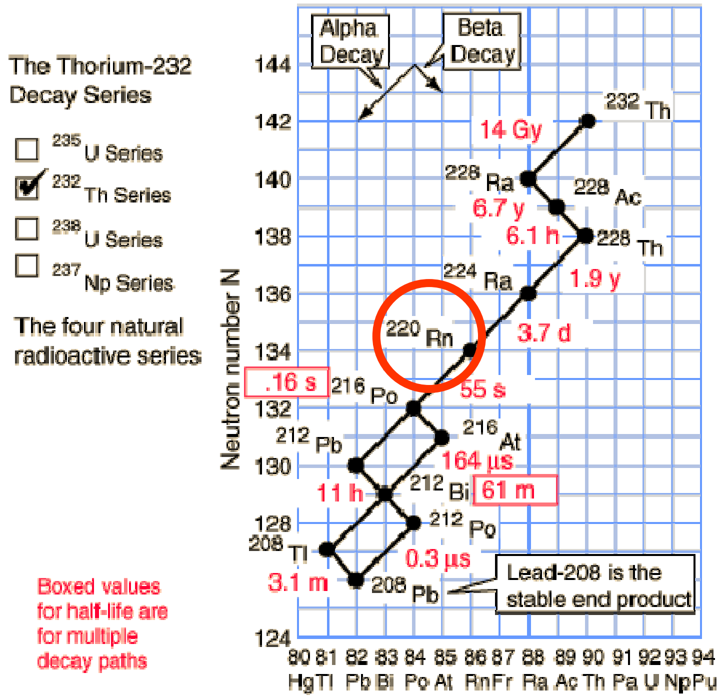
$$D = 0{,}09\mu Sv/hod \Rightarrow 0{,}09\cdot 365\cdot 24\mu Sv/rok = \underline{0{,}788mSv/rok}$$

Radon 2mSv/rok

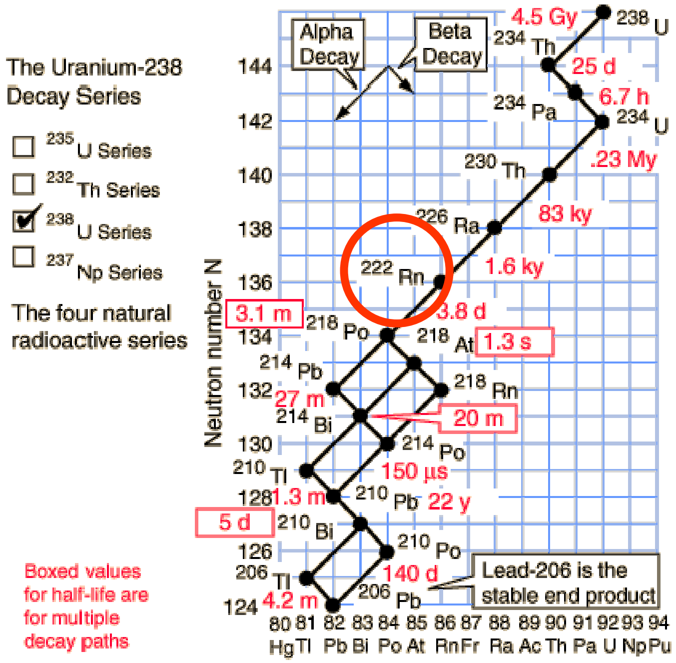
Radon



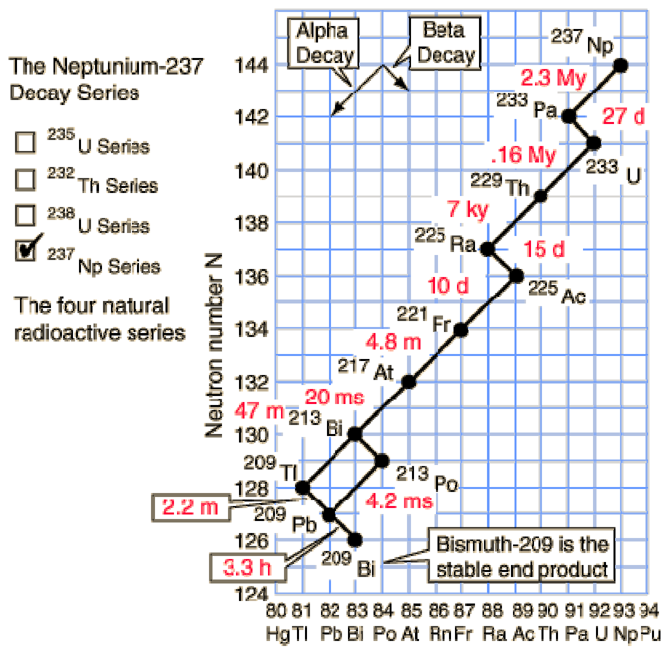
The Uranium-235 Decay Series
235 U Series
232 Th Series
238 U Series
237 Np Series
The four natural radioactive series
This series is traditionally called the Actinium series.
Boxed values for half-life are for multiple decay paths
Alpha Decay
Beta Decay
Lead-207 is the stable end product
Neutron number N



The Thorium-232 Decay Series
235 U Series
232 Th Series
238 U Series
237 Np Series
The four natural radioactive series
Boxed values for half-life are for multiple decay paths
Alpha Decay
Beta Decay
Lead-208 is the stable end product
Neutron number N

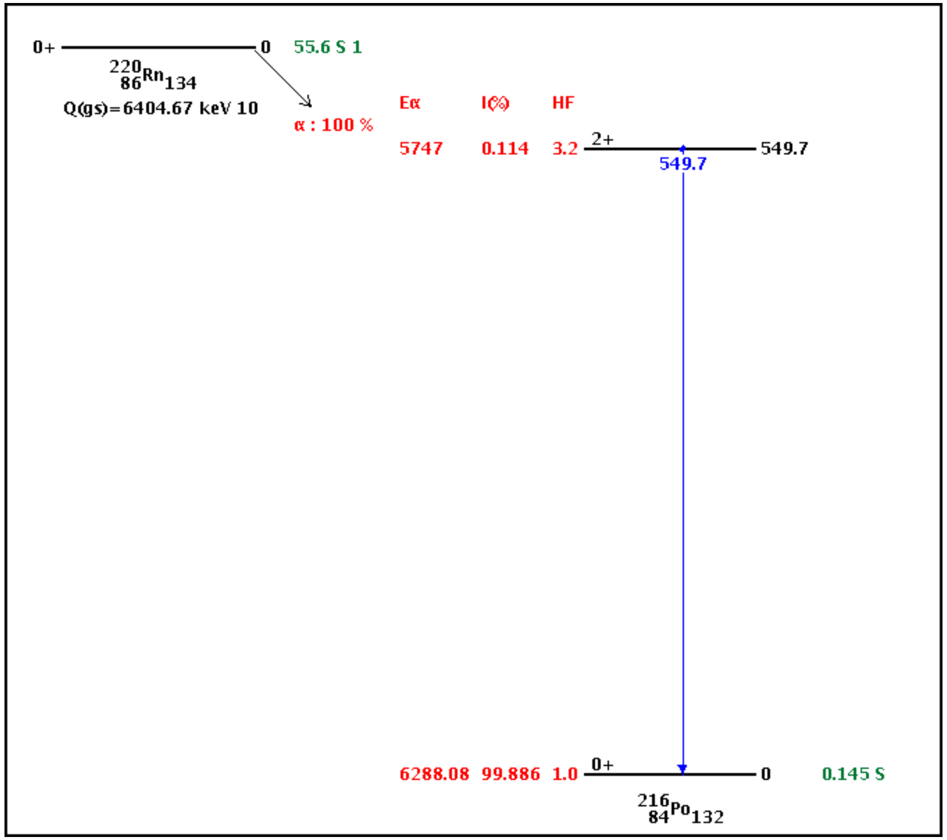


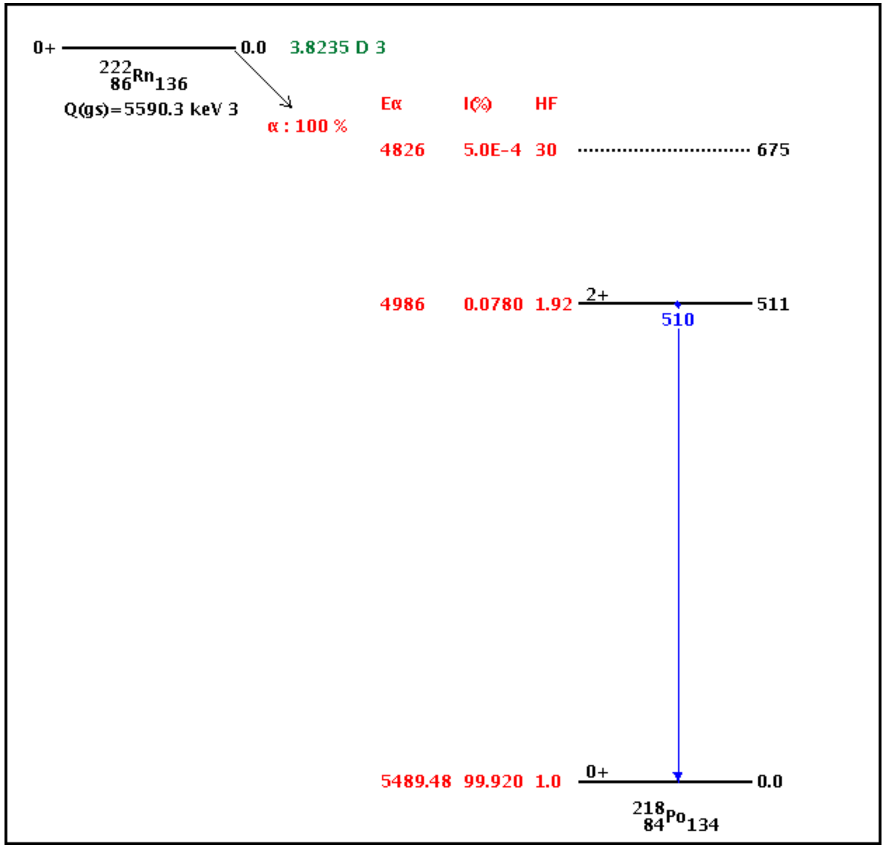
The Uranium-238 Decay Series
235 U Series
232 Th Series
238 U Series
237 Np Series
The four natural radioactive series
Boxed values for half-life are for multiple decay paths
Alpha Decay
Beta Decay
Lead-206 is the stable end product
Neutron number N



The Neptunium-237 Decay Series
235 U Series
232 Th Series
238 U Series
237 Np Series
The four natural radioactive series
Alpha Decay
Beta Decay
Bismuth-209 is the stable end product
Neutron number N

Radon je plyn, vdechujeme ho a alfa částice mohou poškodit plíce





Následky ozáření:

Table of exposure levels and symptoms
Dose-equivalents are presently stated in sieverts:
0.05–0.2 Sv (5–20 REM)
No symptoms.
0.2–0.5 Sv (20–50 REM)
No noticeable symptoms. Red blood cell count decreases temporarily.
0.5–1 Sv (50–100 REM)
Mild radiation sickness with headache and increased risk of infection due to disruption of immunity cells. Temporary male sterility is possible.

1–2 Sv (100–200 REM)
Light radiation poisoning, 10% fatality after 30 days (LD 10/30). Typical symptoms include mild to moderate nausea (50% probability at 2 Sv), with occasional vomiting, beginning 3 to 6 hours after irradiation and lasting for up to one day. This is followed by a 10 to 14 day latent phase, after which light symptoms like general illness and fatigue appear (50% probability at 2 Sv). The immune system is depressed, with convalescence extended and increased risk of infection. Temporary male sterility is common. Spontaneous abortion or stillbirth will occur in pregnant women.
2–3 Sv (200–300 REM)
Moderate radiation poisoning, 35% fatality after 30 days (LD 35/30). Nausea is common (100% at 3 Sv), with 50% risk of vomiting at 2.8 Sv. Symptoms onset at 1 to 6 hours after irradiation and last for 1 to 2 days. After that, there is a 7 to 14 day latent phase, after which the following symptoms appear: loss of hair all over the body (50% probability at 3 Sv), fatigue and general illness. There is a massive loss of leukocytes (white blood cells), greatly increasing the risk of infection. Permanent female sterility is possible. Convalescence takes one to several months.
3–4 Sv (300–400 REM)
Severe radiation poisoning, 50% fatality after 30 days (LD 50/30). Other symptoms are similar to the 2–3 Sv dose, with uncontrollable bleeding in the mouth, under the skin and in the kidneys (50% probability at 4 Sv) after the latent phase.
180 Sv (18,000 REM) to his upper body in an accident at Los Alamos, New Mexico, USA on 30 December 1958 survived for 36 hours.

Následky ozáření:

4–6 Sv (400–600 REM)

Acute radiation poisoning, 60% fatality after 30 days (LD 60/30). Fatality increases from 60% at 4.5 Sv to 90% at 6 Sv (unless there is intense medical care). Symptoms start half an hour to two hours after irradiation and last for up to 2 days. After that, there is a 7 to 14 day latent phase, after which generally the same symptoms appear as with 3-4 Sv irradiation, with increased intensity. Female sterility is common at this point. Convalescence takes several months to a year. The primary causes of death (in general 2 to 12 weeks after irradiation) are infections and internal bleeding.

6–10 Sv (600–1,000 REM)

Acute radiation poisoning, near 100% fatality after 14 days (LD 100/14). Survival depends on intense medical care. Bone marrow is nearly or completely destroyed, so a bone marrow transplant is required. Gastric and intestinal tissue are severely damaged. Symptoms start 15 to 30 minutes after irradiation and last for up to 2 days. Subsequently, there is a 5 to 10 day latent phase, after which the person dies of infection or internal bleeding. Recovery would take several years and probably would never be complete.

Devair Alves Ferreira received a dose of approximately 7.0 Sv (700 REM) during the Goiânia accident and survived, partially due to his fractionated exposure.

10–50 Sv (1,000–5,000 REM)

Acute radiation poisoning, 100% fatality after 7 days (LD 100/7). An exposure this high leads to spontaneous symptoms after 5 to 30 minutes. After powerful fatigue and immediate nausea caused by direct activation of chemical receptors in the brain by the irradiation, there is a period of several days of comparative well-being, called the latent (or "walking ghost") phase[*citation needed*]. After that, cell death in the gastric and intestinal tissue, causing massive diarrhea, intestinal bleeding and loss of water, leads to water-electrolyte imbalance. Death sets in with delirium and coma due to breakdown of circulation. Death is currently inevitable; the only treatment that can be offered is pain therapy.

Louis Slotin was exposed to approximately 21 Sv in a criticality accident on 21 May 1946, and died nine days later on 30 May. At this dose the skin can be damaged. Here is a photo of a man who received a 10 to 20 Gy gamma whole body dose as a result of an industrial accident. He died about 10 days after the photo was taken, about 30 days after the event.

More than 50 Sv (>5,000 REM)

A worker receiving 100 Sv (10,000 REM) in an accident at Wood River, Rhode Island, USA on 24 July 1964 survived for 49 hours after exposure, and an operator receiving between 60 and 180 Sv (18,000 REM) to his upper body in an accident at Los Alamos, New Mexico, USA on 30 December 1958 survived for 36 hours.