Univerza v Ljubljani
Fakulteta za matematiko in fiziko

MODERNA FIZIKA

Izbor povzetkov in interaktivnih vsebin

Študijsko gradivo

Andrej Zorko
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

Kazalo vsebine

Kazalo vsebine

Kvantna mehanika 4: Gibanje v 3D

Kvantna mehanika 5: Molekule

Statistična fizika

Trdna snov

Kazalo vsebine

Jedrska fizika

Osnovni delci

Kazalo interaktivnih in video vsebin

Univerza *v Ljubljani*
Fakulteta za *matematiko in fiziko*

MODERNA FIZIKA

Relativnost 1

Transformacija prostora-časa

Andrej Zorko
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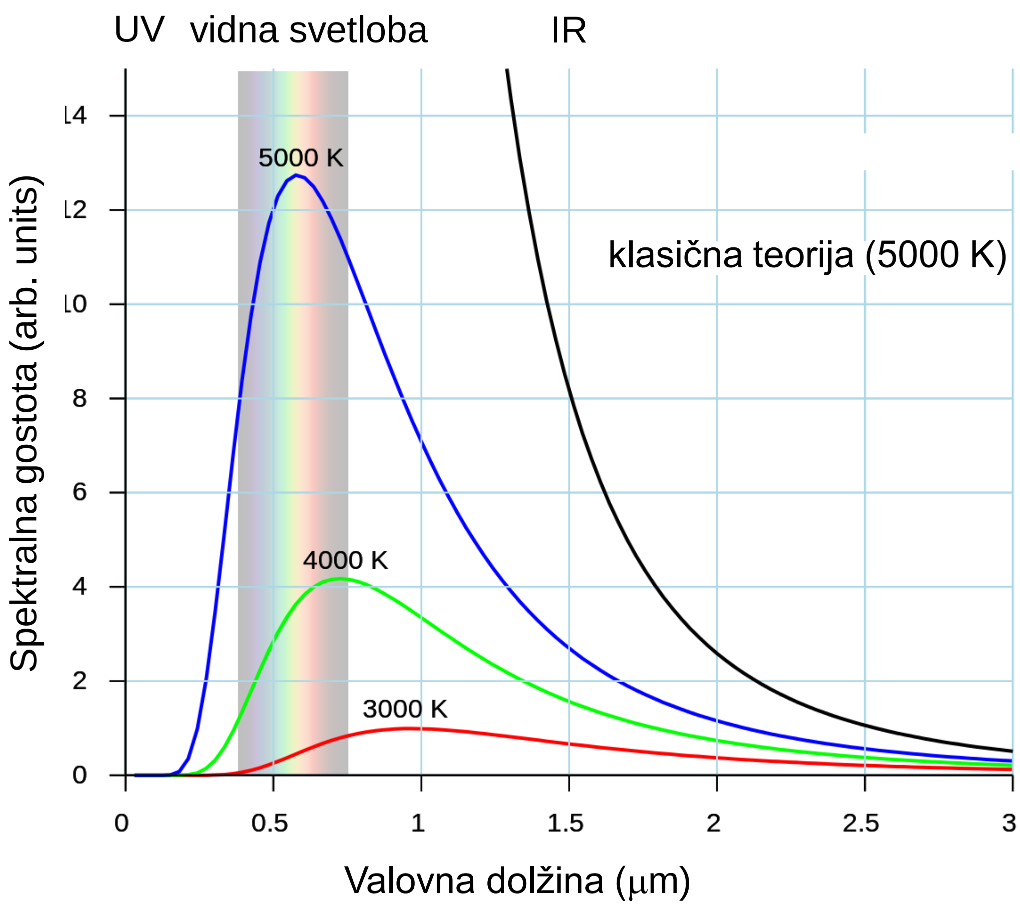
1.1 Uvod v moderno fiziko

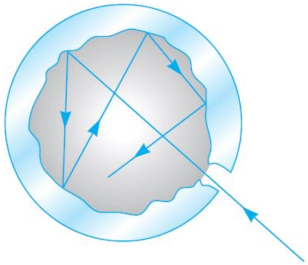
- Sevanje črnega telesa:
  kvantizacija energijskih nivojev



The Nobel Prize in Physics 1918

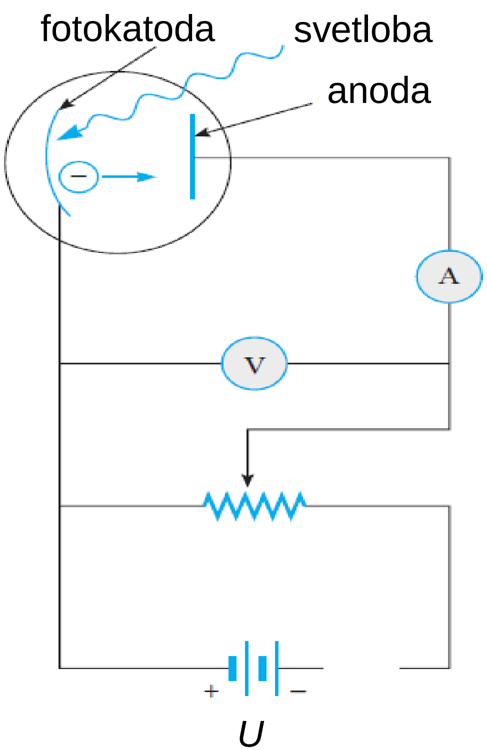
Max Karl Ernst Ludwig Planck
Prize share: 1/1

The Nobel Prize in Physics 1918 was awarded to Max Planck *"in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta"*.

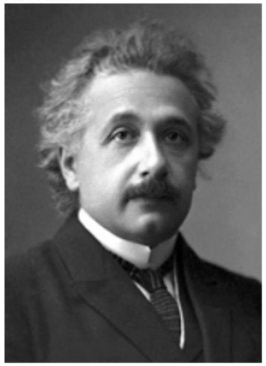


Vir: internet

- Fotoefekt: svetloba kot delci (fotoni)

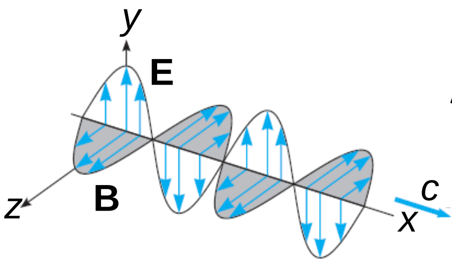


The Nobel Prize in Physics 1921

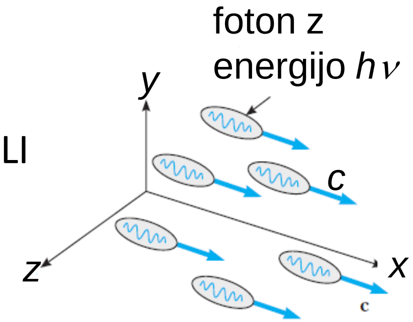


Albert Einstein
Prize share: 1/1

The Nobel Prize in Physics 1921 was awarded to Albert Einstein *"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"*.

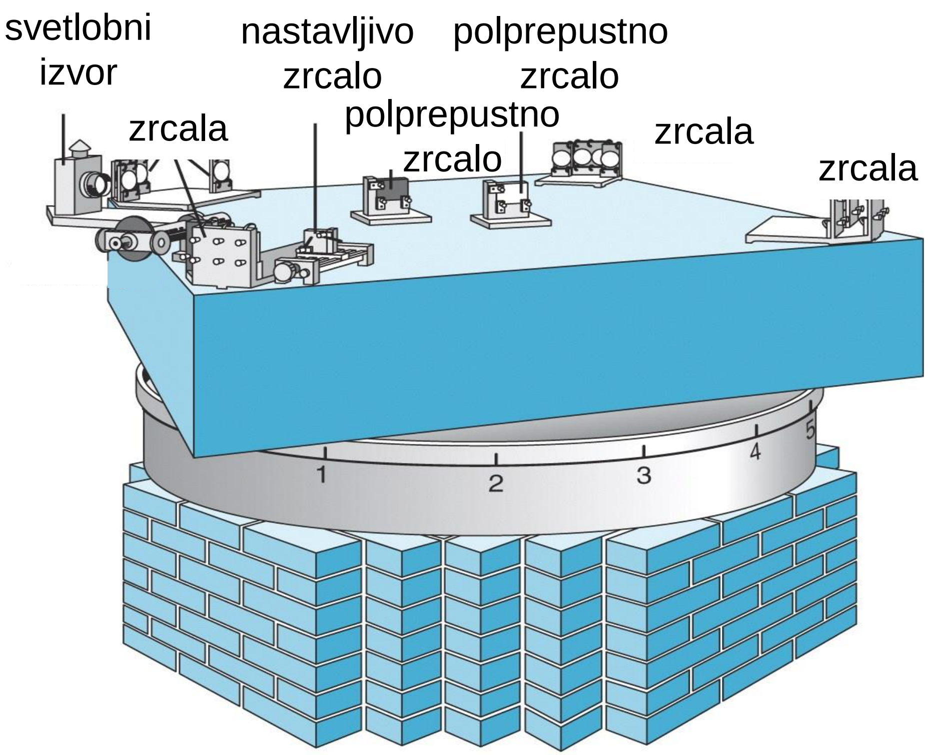


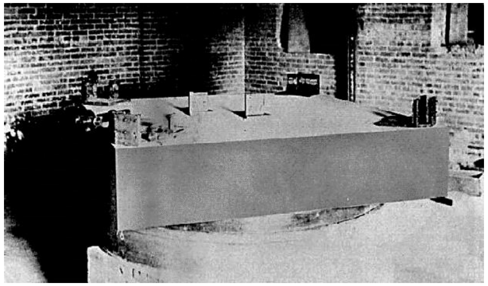
ALI



Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

- Michelson-Morleyev interferometer*:*





The Nobel Prize in Physics 1907

Albert Abraham Michelson
Prize share: 1/1

The Nobel Prize in Physics 2017

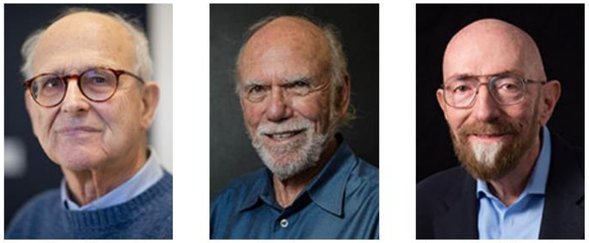
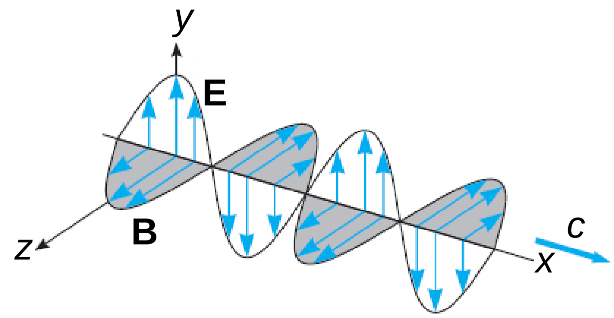


Photo: Bryce Vickmark	Photo: Caltech	Photo: Caltech Alumni Association
Rainer Weiss	**Barry C. Barish**	**Kip S. Thorne**
Prize share: 1/2	**Prize share:** 1/4	**Prize share:** 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves".*

The Nobel Prize in Physics 1907 was awarded to Albert A. Michelson *"for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid".*

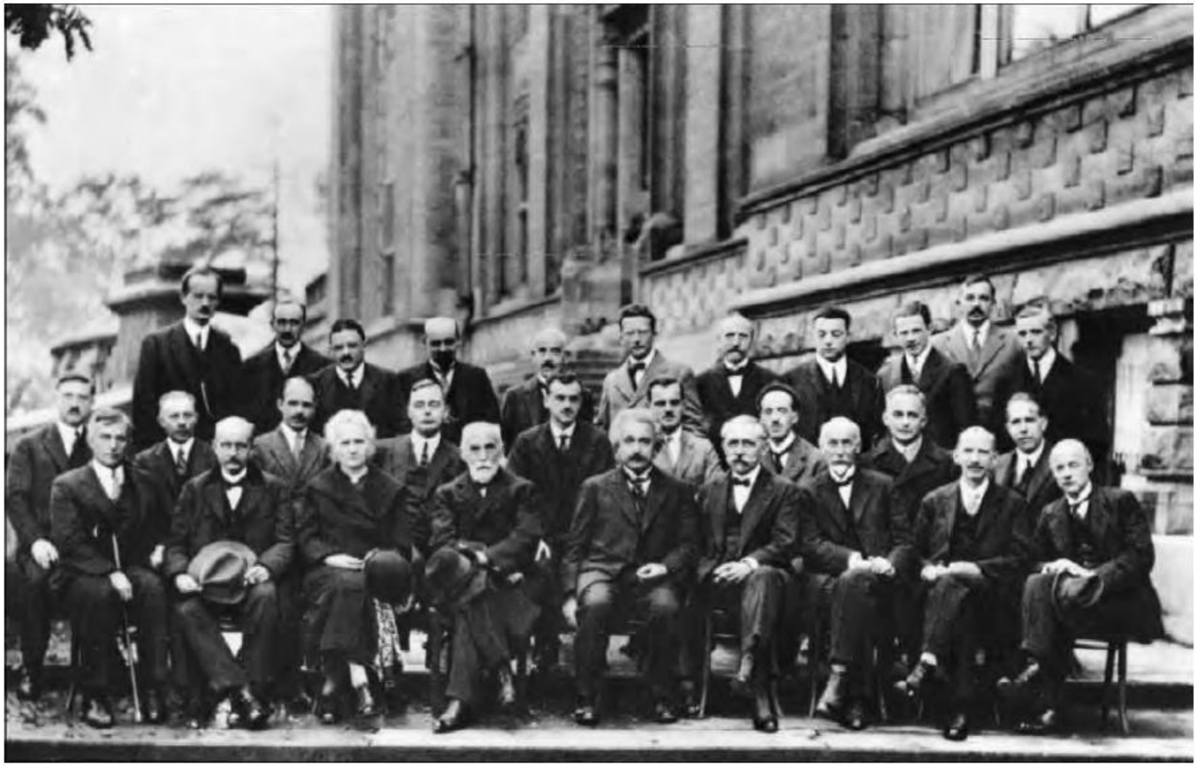


Vir: internet; povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

1.1 Uvod v moderno fiziko

Moderna fizika:

- teorija relativnosti
- kvantna mehanika



Arhitekti moderne fizike zbrani na „the Fifth International Congress of Physics“ (Bruselj, 1927):

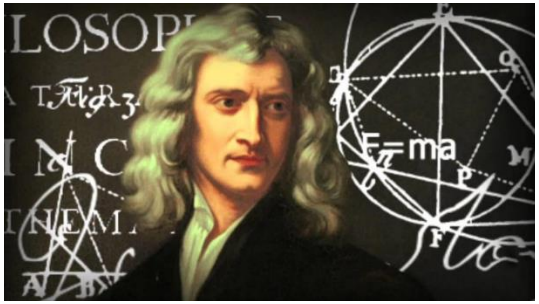
- 15 Nobelovih nagrajencev iz fizike
- 3 Nobelovi nagrajenci iz kemije

1. A. Piccard
2. E. Henriot
3. P. Ehrenfest
4. E. Herzen
5. Th. de Donder
6. E. Schroedinger
7. E. Verschaffelt
8. W. Pauli
9. W. Heisenberg
10. R.H. Fowler
11. L. Brillouin
12. P. Debye
13. M. Knudsen
14. W.L. Bragg
15. H.A. Kramers
16. P.A.M. Dirac
17. A.H. Compton
18. L.V. de Broglie
19. M. Born
20. N. Bohr
21. I. Langmuir
22. M. Planck
23. M. Curie
24. H.A. Lorentz
25. A. Einstein
26. P. Langevin
27. C.E. Guye
28. C.T.R. Wilson
29. O.W. Richardson

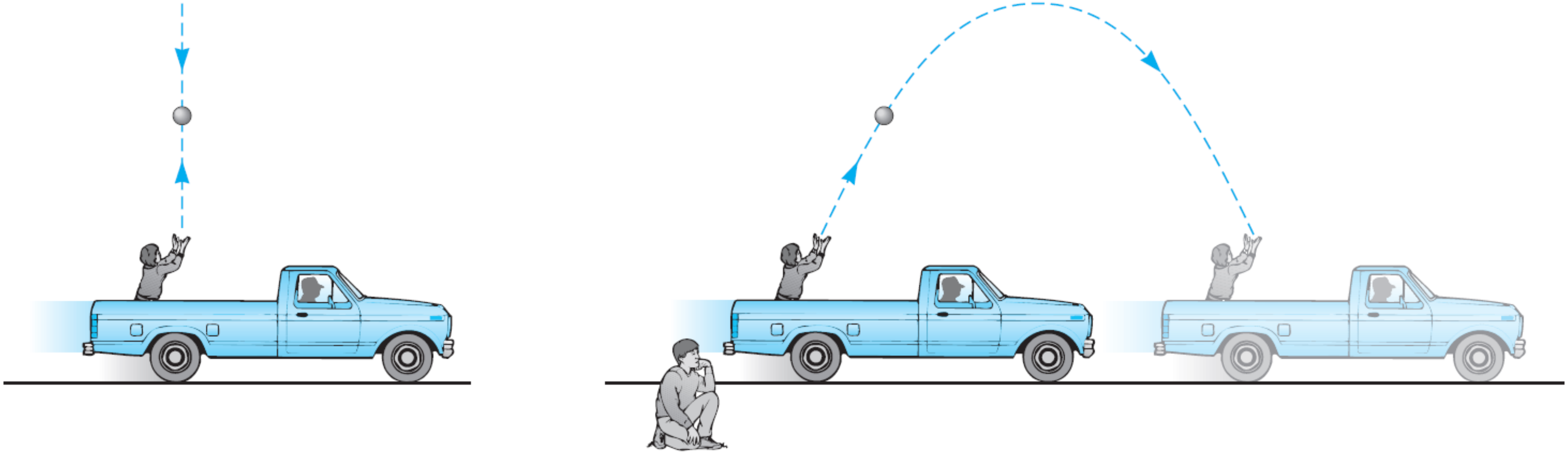
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

1.2 Klasična relativnost

- Invariantnost zakonov mehanike v inercialnih sistemih:

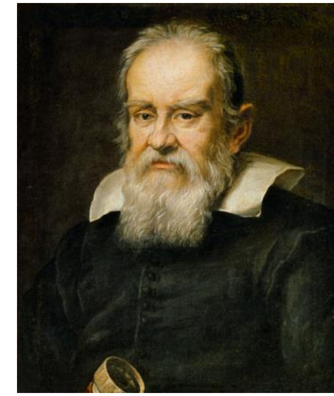


Isaac Newton

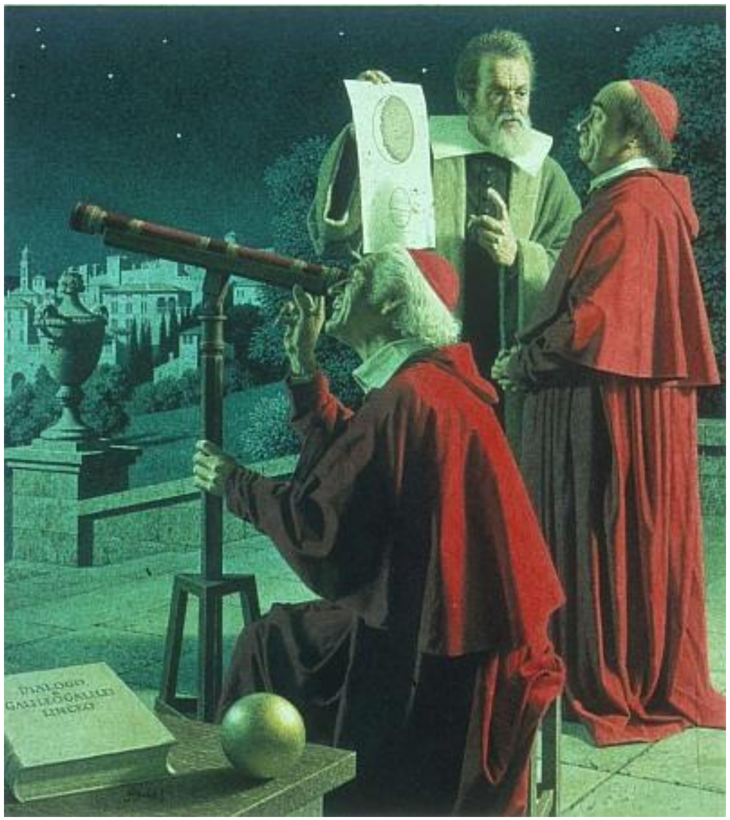


Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

- Relativno gibanje: opazovalec meri le relativno gibanje!



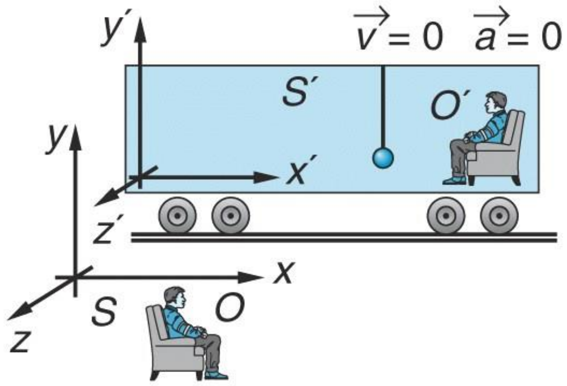
Galileo Galilei

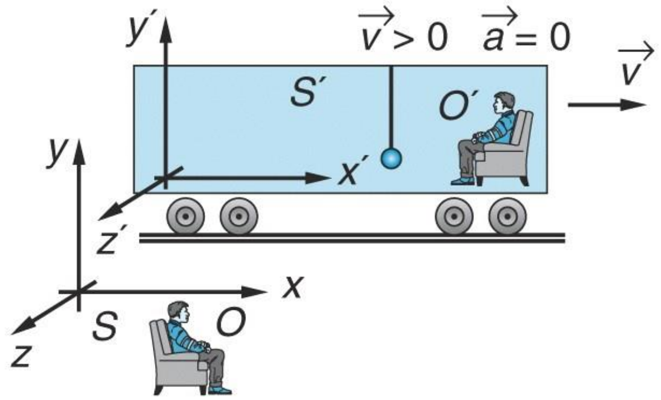


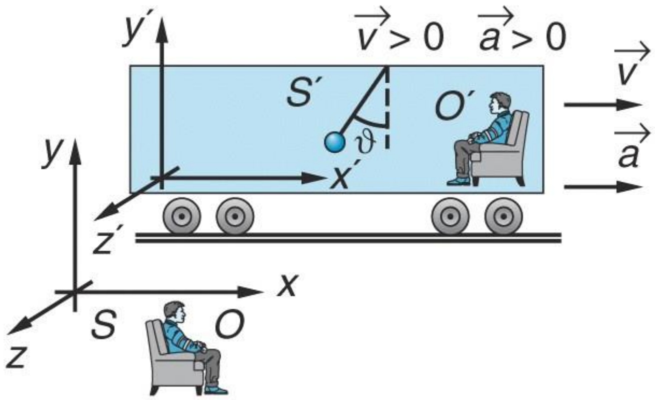
Vir: internet

1.2 Klasična relativnost

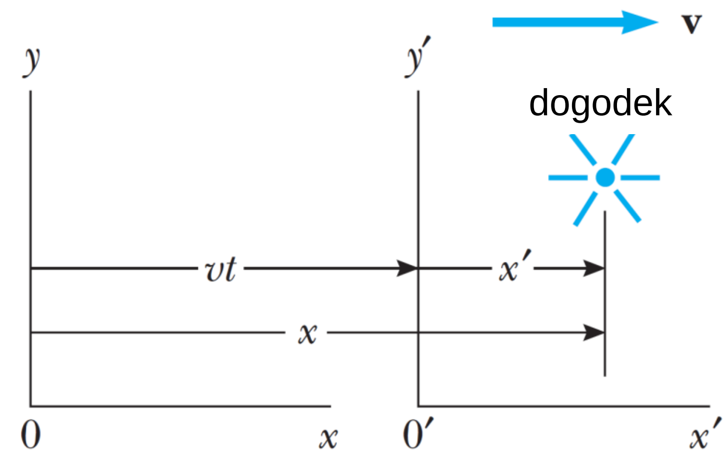
- Princip relativnosti: opazovalec ne razlikuje med mirovanjem in enakomernim gibanjem!







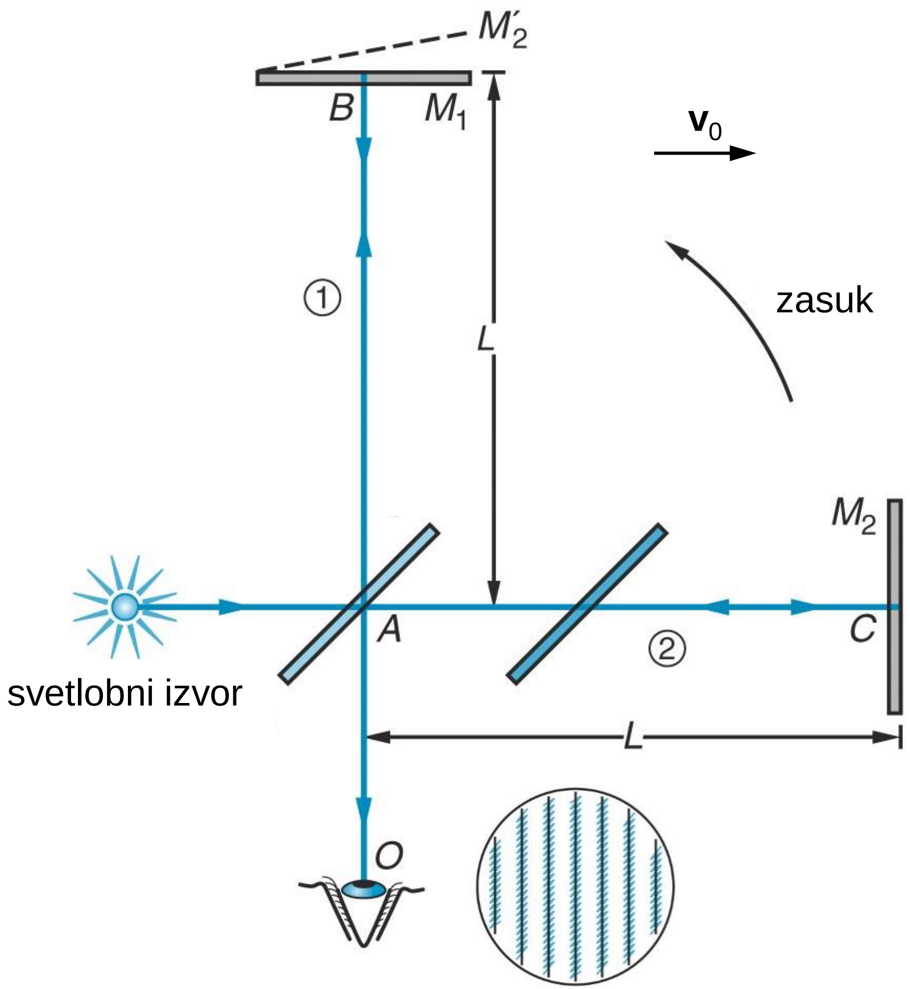
- Galilejeve transformacije: homogenost prostora, absolutnost časa



Vir: povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

1.3 Michelson-Morleyev eksperiment

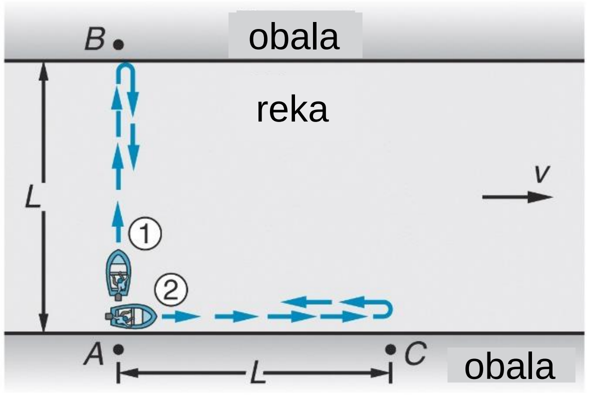
- Hitrost svetlobe: Galileijeva transformacija



$$t_1 = \frac{2L}{c\sqrt{1-v_0^2/c^2}} = 2L\gamma = \frac{2L}{c}\left(1+\frac{1}{2}\frac{v_0^2}{c^2}\right)$$

$$t_2 = \frac{L}{c+v_0} + \frac{L}{c-v_0} = \frac{2L}{c(1-v_0^2/c^2)}$$
$$= \frac{2L}{c}\gamma^2 = \frac{2L}{c}\left(1+\frac{v_0^2}{c^2}\right)$$

$$\gamma = \frac{1}{\sqrt{1-v_0^2/c^2}}$$



Vir: povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

1.4 Posebna teorija relativnosti

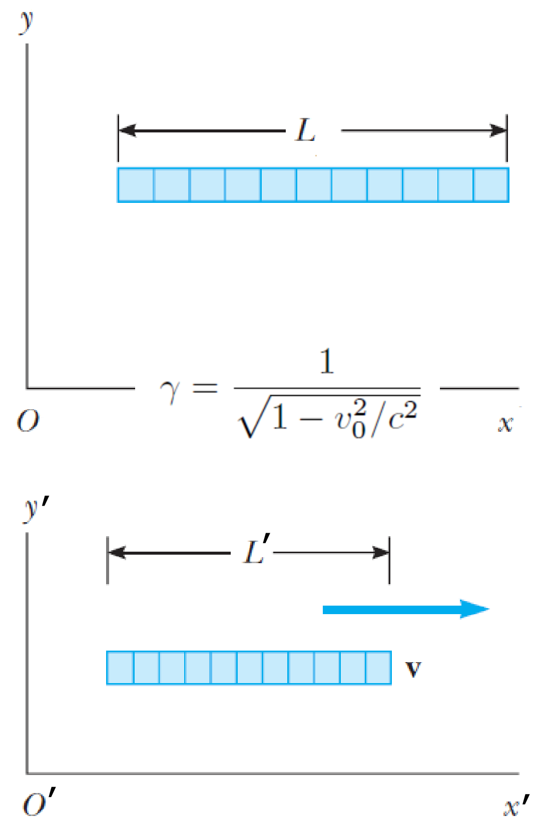
- G. F. Fitzgerald in H. A. Lorentz:

kontrakcija dolžine (ad hoc predpostavka, l. 1890)

$$L' = \frac{L}{\gamma}$$

$$t_2 = \frac{2L'}{c}\gamma^2 = \frac{2L}{c}\gamma = t_1$$

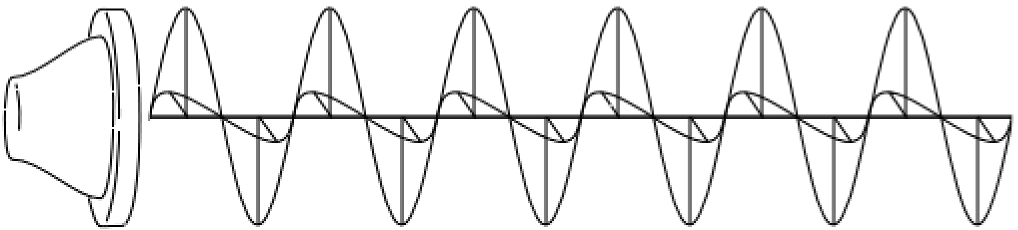
$$\gamma = \frac{1}{\sqrt{1 - v_0^2/c^2}}$$



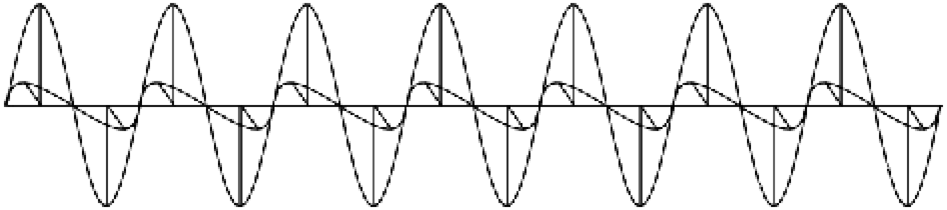
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

1.4 Posebna teorija relativnosti

- Einsteinov miselni eksperiment: lovljenje svetlobe



mirujoč opazovalec



„surfer“

Vir: internet

1.4 Posebna teorija relativnosti

annalen der physik

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Article

Zur Elektrodynamik bewegter Körper

A. Einstein

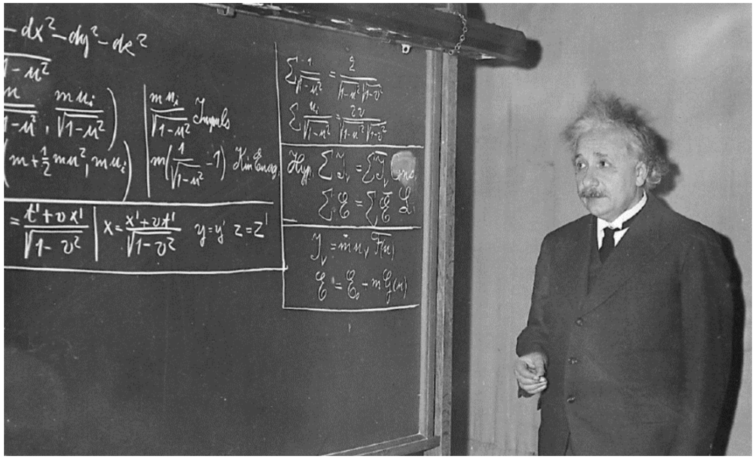
$$\tau = \beta\left(t - \frac{v}{V^2}x\right),$$
$$\xi = \beta(x - vt),$$
$$\eta = y,$$
$$\zeta = z,$$

$$\beta = \frac{1}{\sqrt{1 - \left(\frac{v}{V}\right)^2}},$$

- Einsteinova postulata:

  1. Princip relativnosti: zakoni fizike so enaki v vseh inercialnih sistemih!

  2. Konstantnost hitrosti svetlobe: hitrost svetlobe je v vseh inercialnih sistemih enaka c!

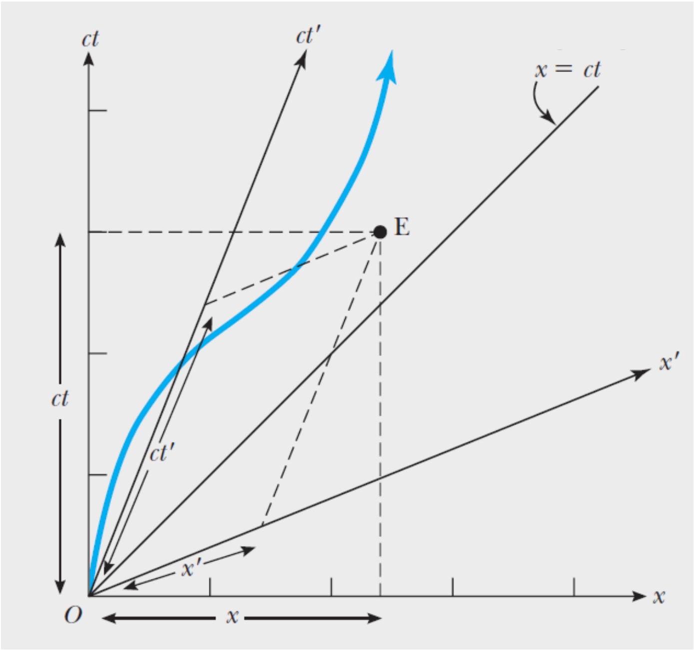


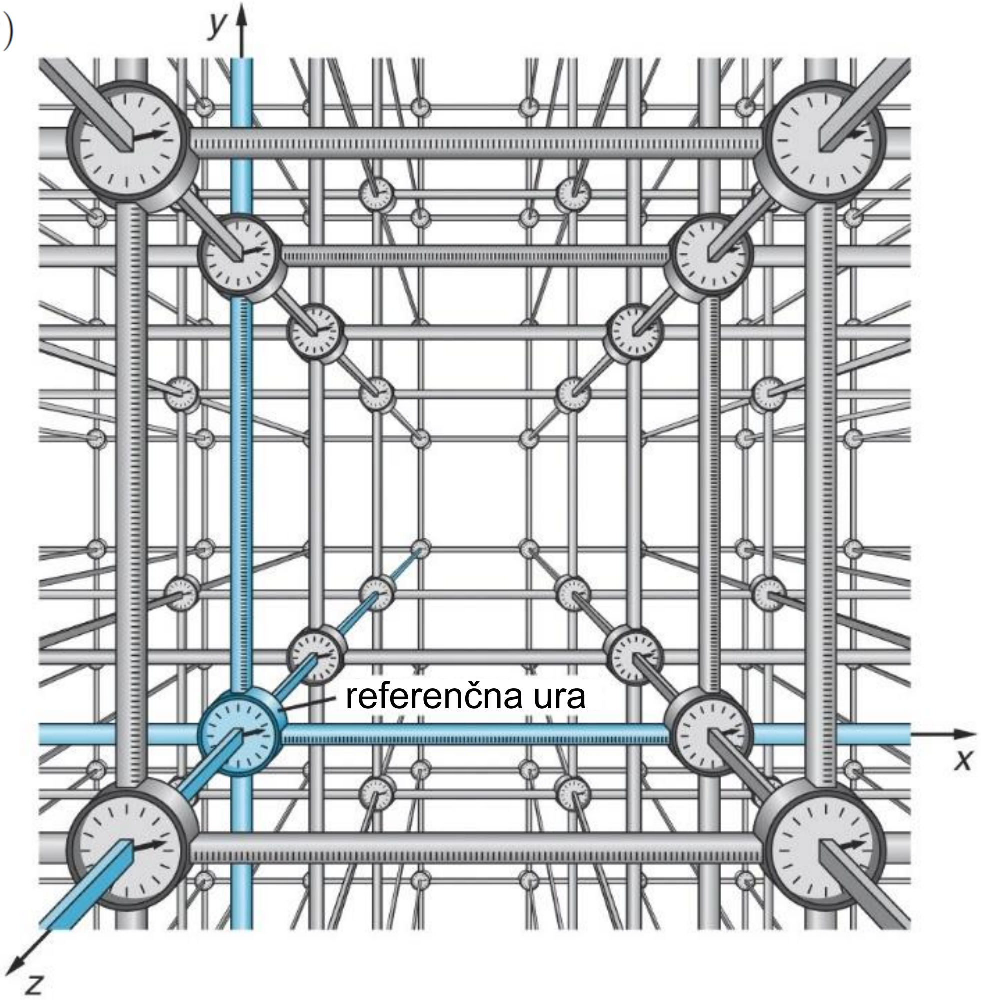
Albert Einstein

Vir: A. Einstein, Ann. Physik **322**, 891 (1905); internet

1.4 Posebna teorija relativnosti

- Koncepti relativnosti:
  1. dogodek: vektor četverec $x^{\mu} = (ct, x, y, z)$
  2. opazovalec
  3. prostor umerjen, ure sinhronizirane znotraj določenega sistema
  4. diagram Minkowskega (svetovnica)

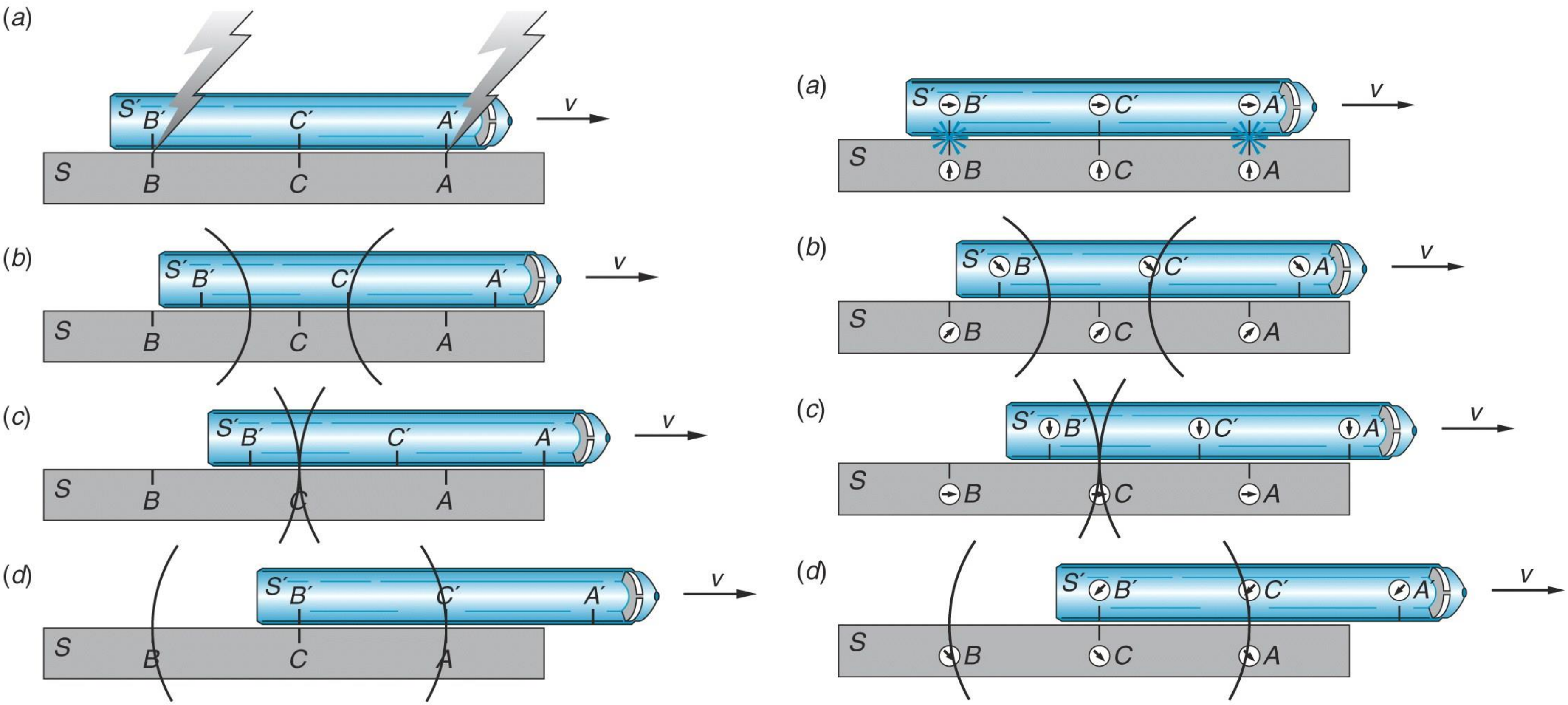




Vir: povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

1.5 Posledice posebne teorije relativnosti

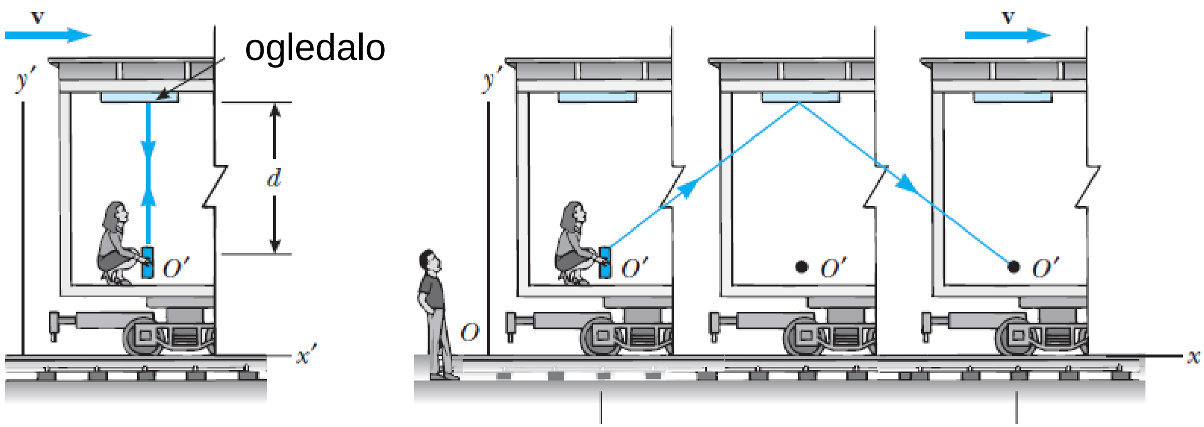
- Relativnost simultanosti: simultanost NI absoluten koncept!

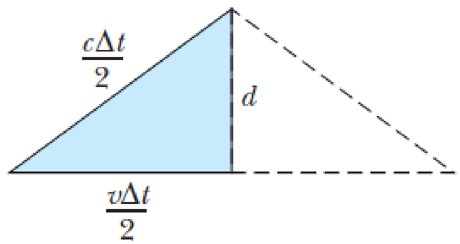


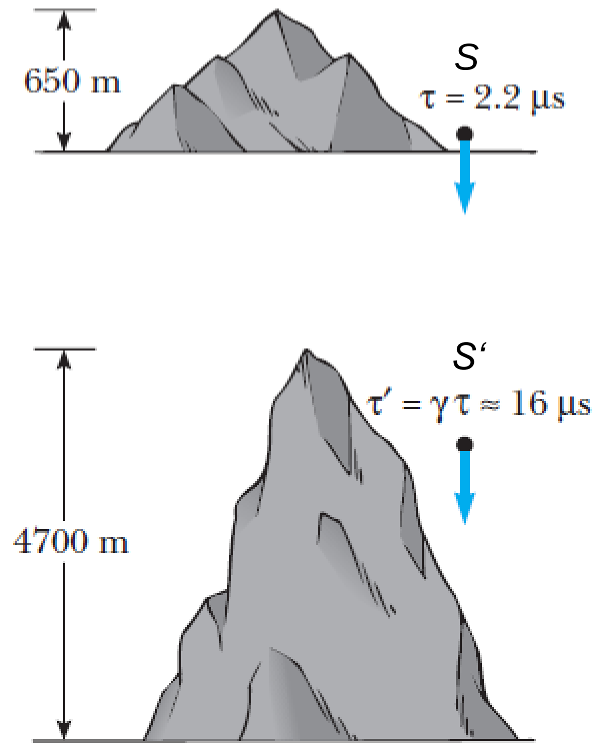
SIMULACIJA

Vir: povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

- Podaljšanje (dilatacija) časa: lastni čas med dogodkoma na istem mestu je najkrajši!



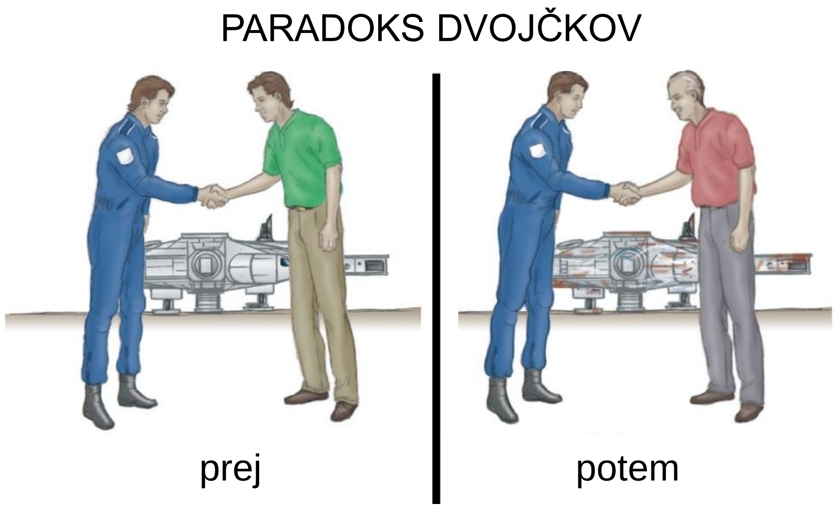




Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

1.5 Posledice posebne teorije relativnosti

- Podaljšanje (dilatacija) časa: lastni čas med dogodkoma na istem mestu je najkrajši!

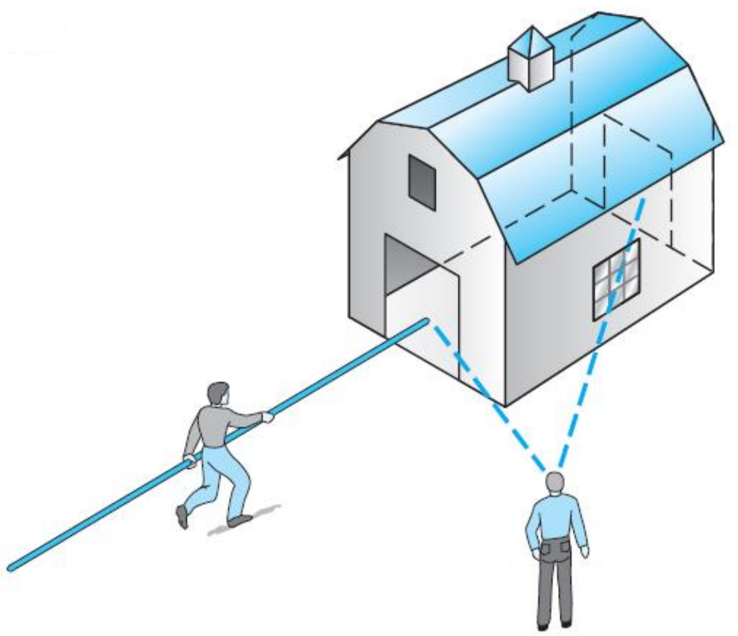


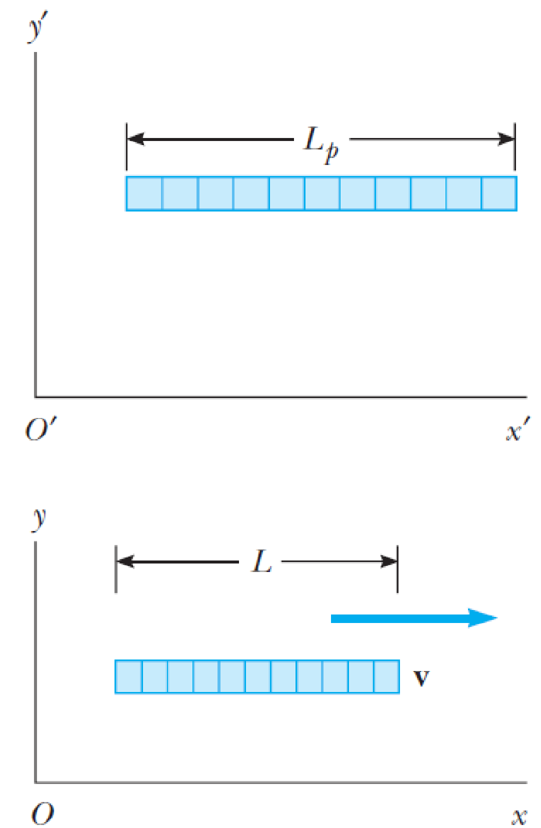
SIMULACIJA

Vir: internet

1.5 Posledice posebne teorije relativnosti

- Skrajšanje (kontrakcija) dolžine: lastna dolžina predmeta, ki miruje, je najdaljša!

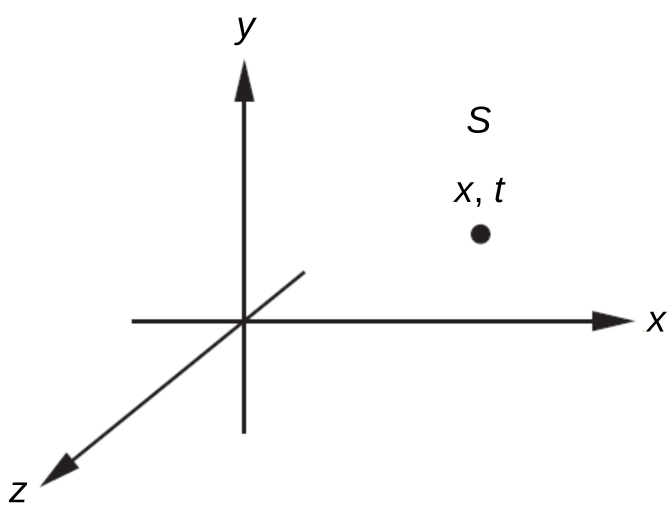


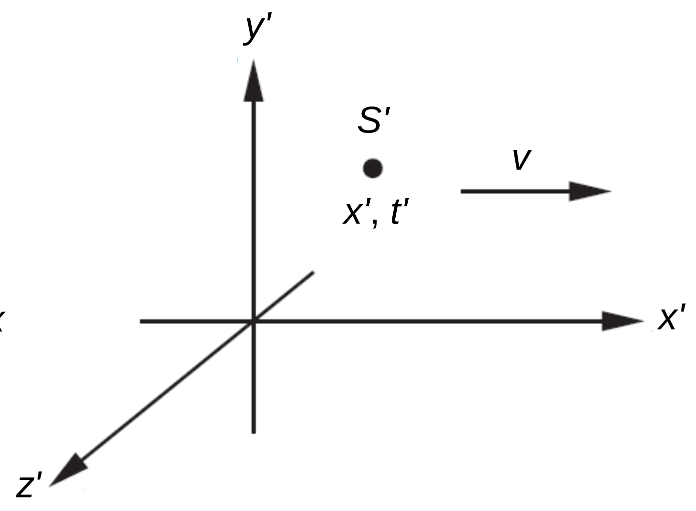


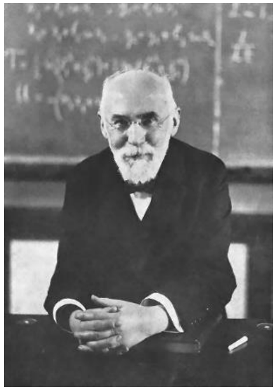
SIMULACIJA

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

1.6 Lorentzova transformacija







Henrik Lorentz

$$x = \gamma_0 \left(x' + \beta c t'\right) \qquad x' = \gamma_0 \left(x - \beta c t\right)$$

$$y = y' \qquad y' = y$$

$$z = z' \qquad z' = z$$

$$ct = \gamma_0 \left(ct' + \beta x'\right) \qquad ct' = \gamma_0 \left(ct - \beta x\right)$$

$$\gamma_0 = \frac{1}{\sqrt{1 - v_0^2/c^2}}$$

$$\beta = \frac{v_0}{c}$$

- Skalarni produkt: invarianta

$$x^\mu x^\mu = s^2 = (ct)^2 - \left(x^2 + y^2 + z^2\right)$$

Vir: internet

Univerza *v Ljubljani*
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MODERNA FIZIKA

Relativnost 2
Kinematika

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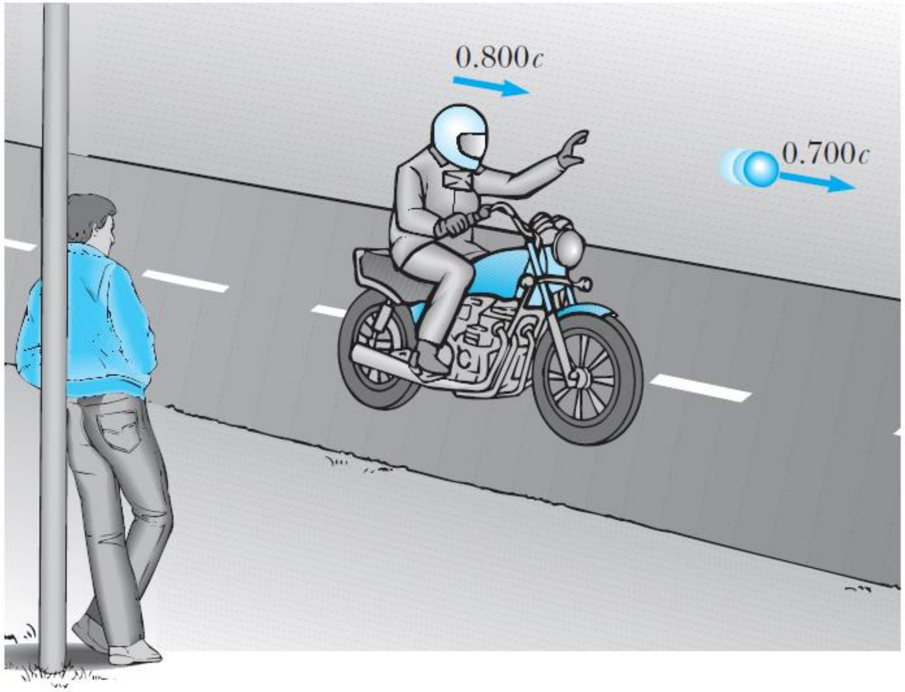
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

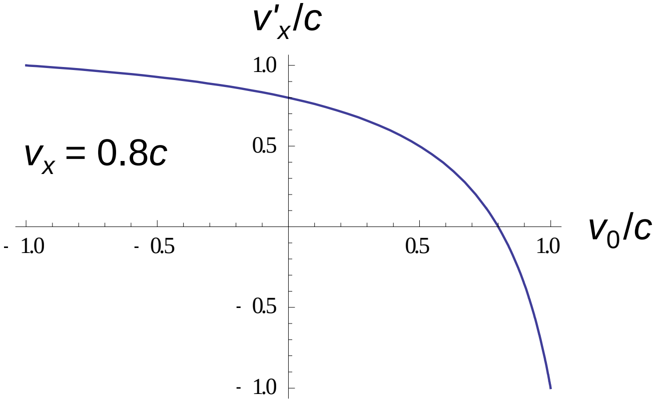
2.1 Transformacija hitrosti

$$v'_x = \frac{v_x - v_0}{1 - \frac{v_0 v_x}{c^2}}$$

$$v'_y = \frac{v_y}{\gamma_0 \left(1 - \frac{v_0 v_x}{c^2}\right)}$$

$$v'_z = \frac{v_z}{\gamma_0 \left(1 - \frac{v_0 v_x}{c^2}\right)}$$

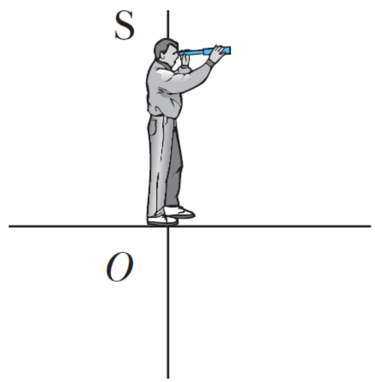


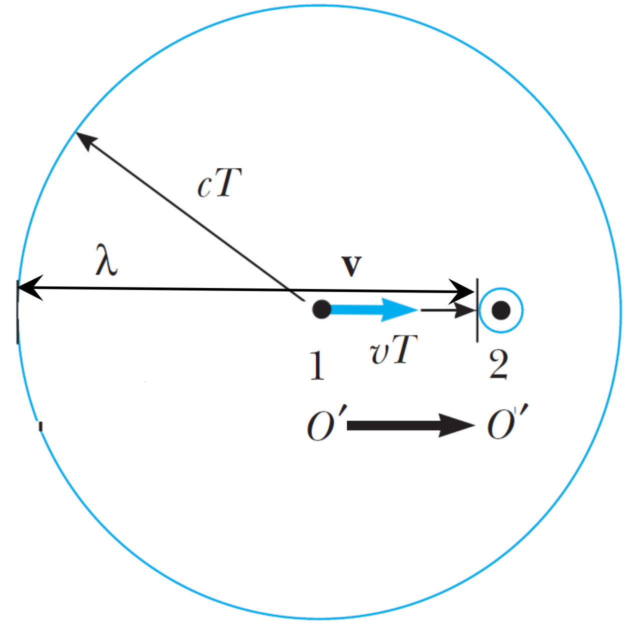


Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

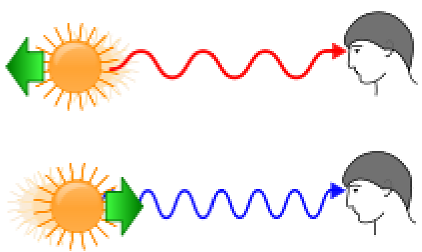
2.2 Relativistični Dopplerjev premik

"I love hearing that lonesome wail of the train whistle as the frequency of the wave changes due to the Doppler effect."





Rdeči premik:



$$\omega' = \gamma_0 \omega \left(1 - \frac{v_0}{c}\cos\theta\right)$$

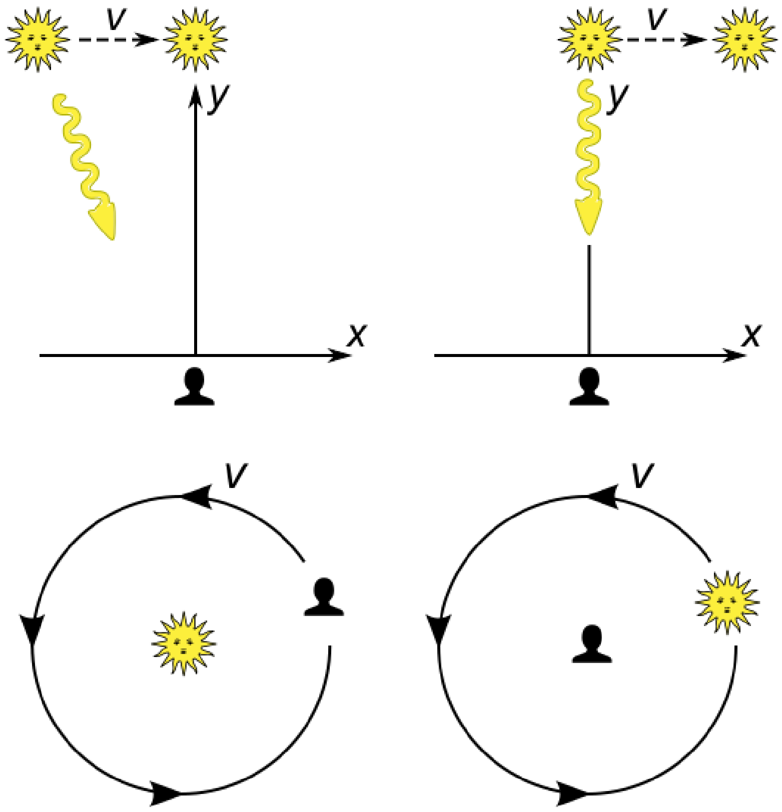
$$\sin\theta' = \frac{\sin\theta}{\gamma_0\left(1 - \frac{v_0}{c}\cos\theta\right)}$$

- Valovni vektor četverec: $k^\mu = \left(\frac{\omega}{c}, k_x, k_y, k_z\right)$

Vir: internet, povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

2.2 Relativistični Dopplerjev premik

- Transverzalni relativistični Dopplerjev premik – smer relativnega gibanja pravokotna na smer širjenja svetlobe:



SIMULACIJA

Vir: internet

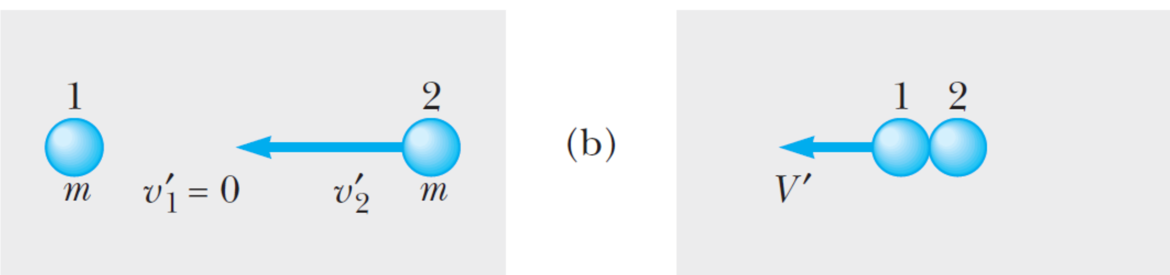
2.3 Relativistična gibalna količina

- „Klasična“ gibalna količina se ne ohranja:

(a)

$$p_{\text{pred}} = mv + m(-v) = 0$$
$$p_{\text{po}} = 0$$

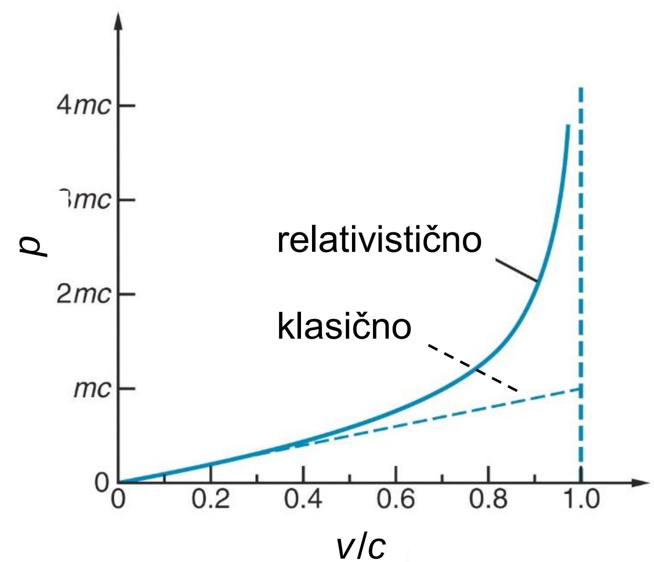
(b)



$$p'_{\text{pred}} = \frac{-2mv}{1 + v^2/c^2}$$
$$p'_{\text{po}} = -2mv$$

- Relativistično:

$$\mathbf{p} = \gamma m \mathbf{v}$$



- Relativistična gibalna enačba:

$$F = \frac{dp}{dt} = \frac{d}{dt}(\gamma m v) = \frac{m}{(1 - v^2/c^2)^{3/2}} \frac{dv}{dt}$$

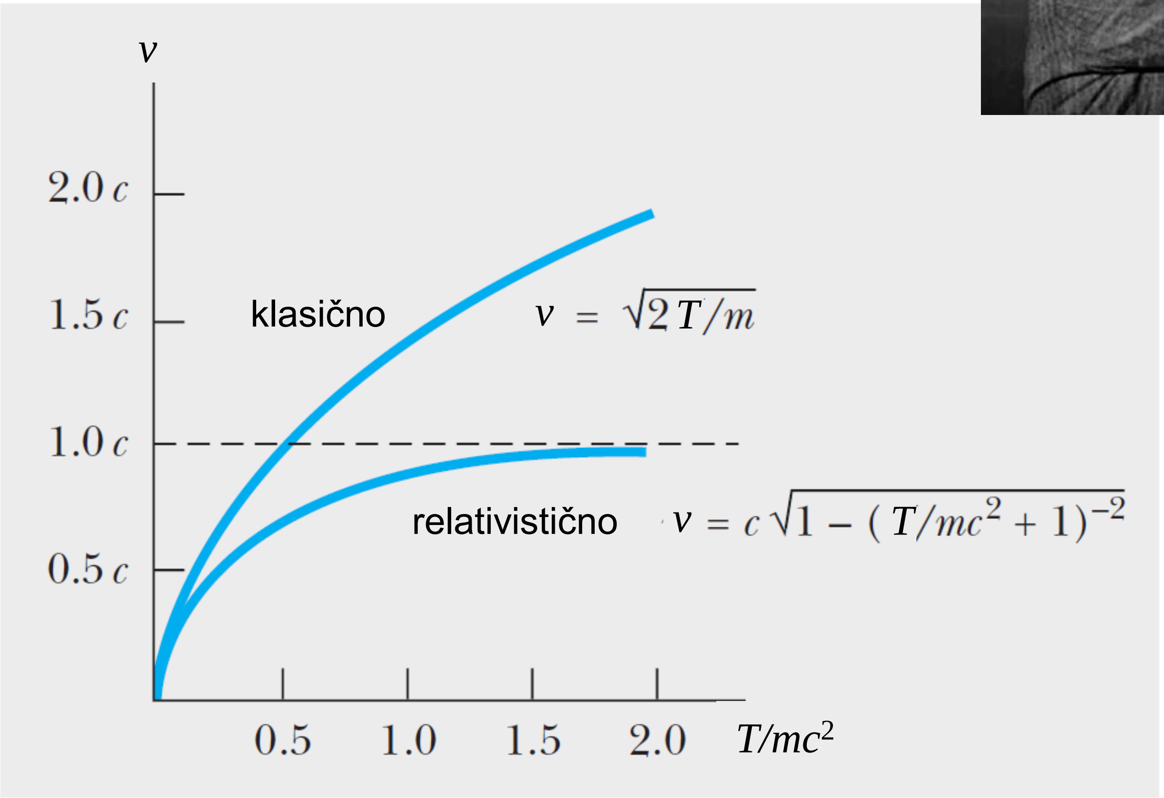
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

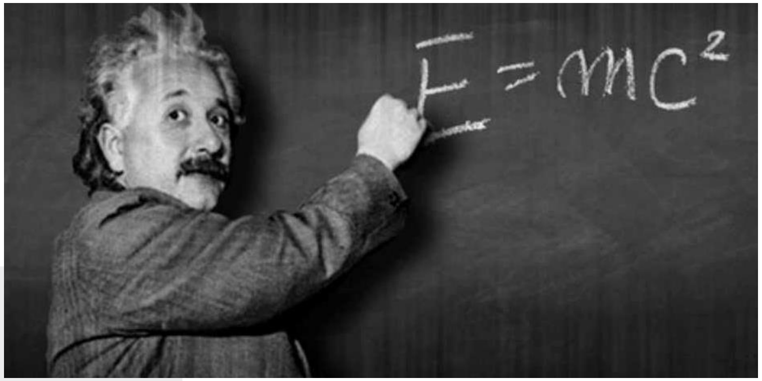
2.4 Relativistična energija

- „Klasična“ (kinetična) energija se ne ohranja!

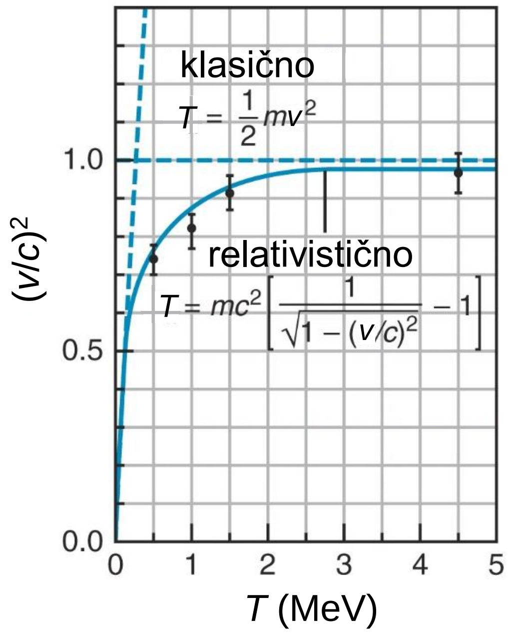
$$T = (\gamma - 1)mc^2$$

$$W = T + mc^2 = \gamma mc^2$$





Albert Einstein



Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

2.5 Vektorji četverci in invariante

- Krajevni vektor četverec

$$x^\mu = (ct, x, y, z)$$

$$\begin{aligned} x' &= \gamma_0 (x - \beta ct) \\ y' &= y \\ z' &= z \\ ct' &= \gamma_0 (ct - \beta x) \end{aligned}$$

$$x^\mu x^\mu = s^2 = (ct)^2 - (x^2 + y^2 + z^2)$$

- Valovni vektor četverec

$$k^\mu = \left(\frac{\omega}{c}, k_x, k_y, k_z\right)$$

$$\begin{aligned} k'_x &= \gamma_0 \left(k_x - \beta \frac{\omega}{c}\right) \\ k'_y &= k_y \\ k'_z &= k_z \\ \frac{\omega'}{c} &= \gamma_0 \left(\frac{\omega}{c} - \beta k_x\right) \end{aligned}$$

$$k^\mu k^\mu = \left(\frac{\omega}{c}\right)^2 - (k_x^2 + k_y^2 + k_z^2) = 0$$

- Četverec gibalne količine

$$p^\mu = \left(\frac{W}{c}, p_x, p_y, p_z\right)$$

$$\begin{aligned} p'_x &= \gamma_0 \left(p_x - \beta \frac{W}{c}\right) \\ p'_y &= p_y \\ p'_z &= p_z \\ \frac{W'}{c} &= \gamma_0 \left(\frac{W}{c} - \beta p_x\right) \end{aligned}$$

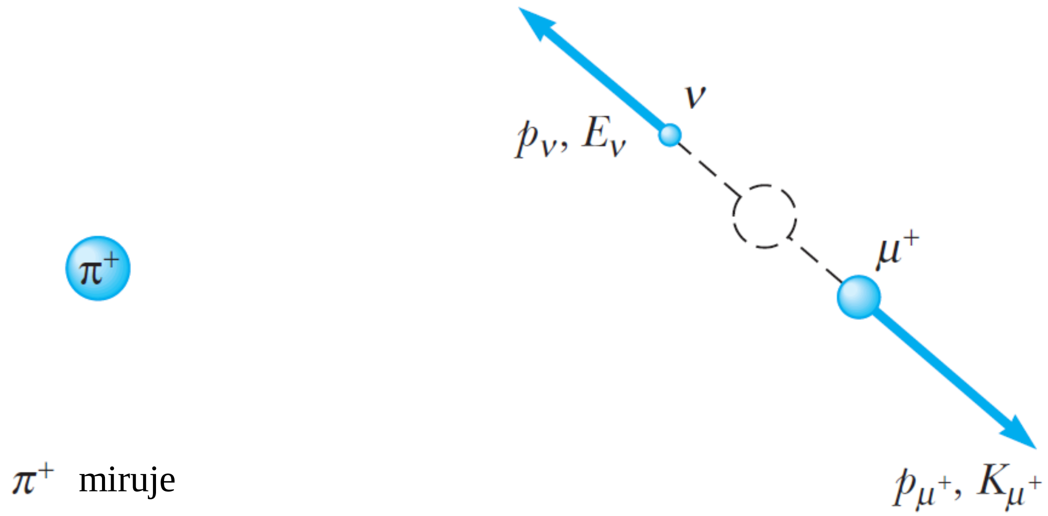
$$p^\mu p^\mu = \left(\frac{W}{c}\right)^2 - (p_x^2 + p_y^2 + p_z^2) = m^2 c^2$$

2.6 Sistem delcev

➢ Razpad piona: $\pi^+ \rightarrow \mu^+ + \nu$

PREJ

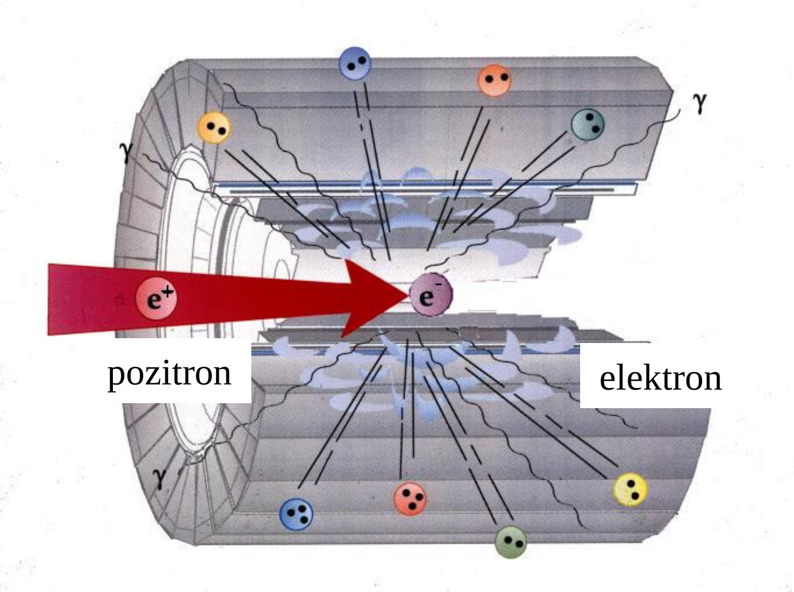
POTEM

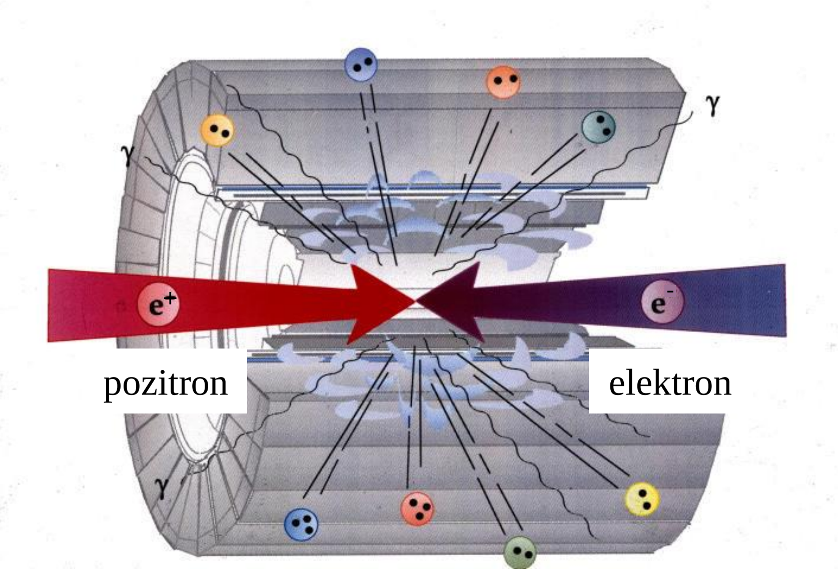


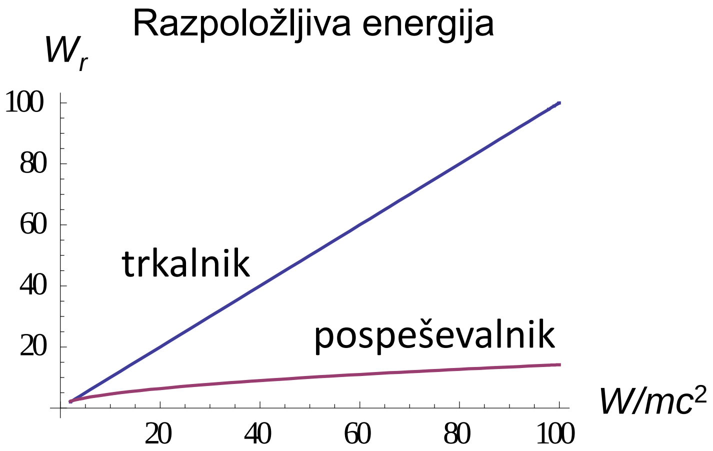
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

2.6 Sistem delcev

POSPEŠEVALNIKI vs. TRKALNIKI







Vir: internet

Univerza v Ljubljani
Fakulteta za *matematiko in fiziko*

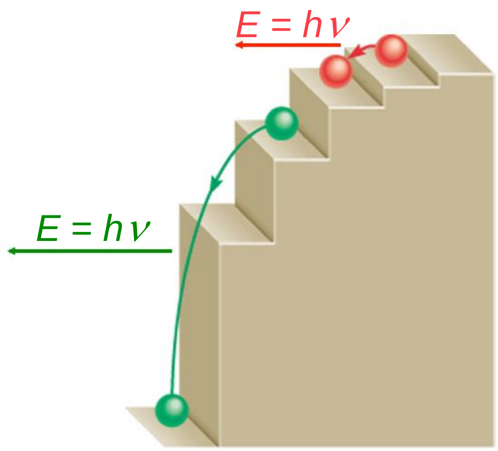
MODERNA FIZIKA

Kvantna mehanika 1
Valovanje ali delci?

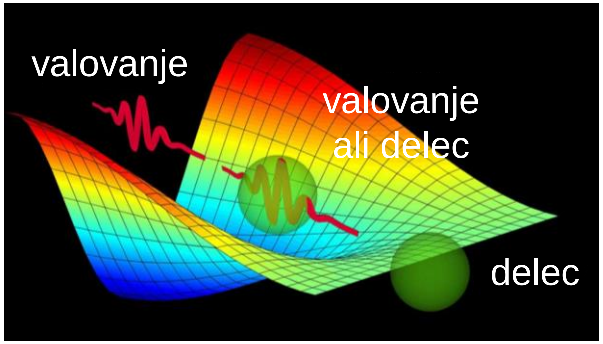
Andrej Zorko
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

3.1 Uvod v kvantno mehaniko

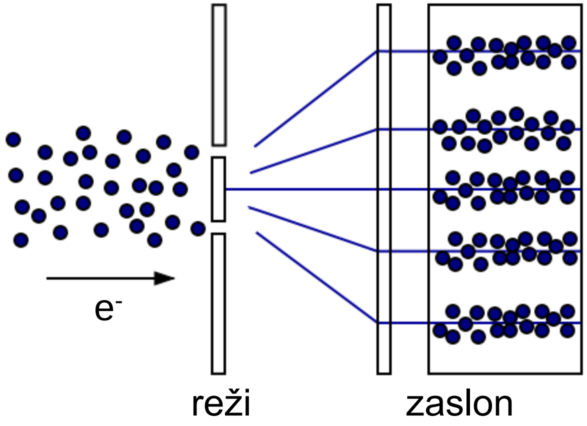
➢ V čem je kvantna fizika nekonvencionalna?



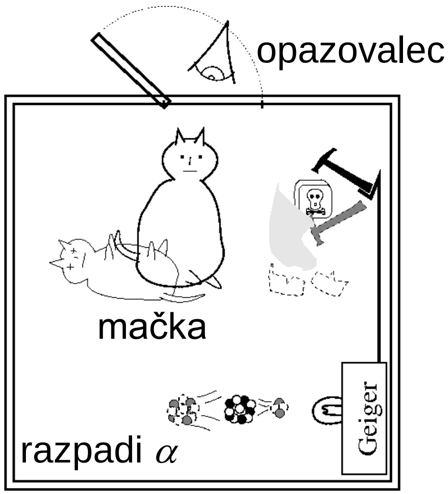
1. kvantizacija fizikalnih količin



2. dualnost delec - valovanje



3. verjetnostne napovedi



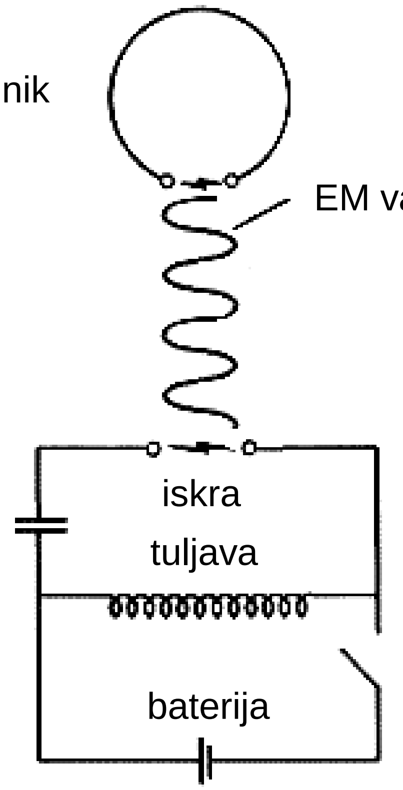
4. problem opazovalca

➢ NAČELO KORESPONDENCE

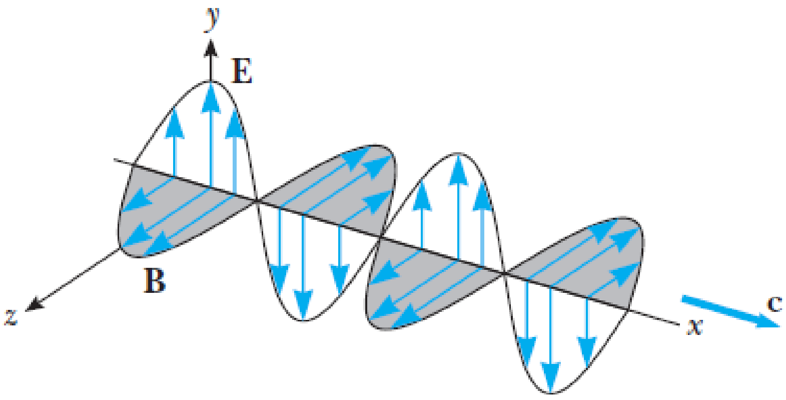
Vir: internet

3.2 Svetloba – valovanje ali delci?

- Hertzov poskus (l. 1887): EM valovanje in nihajoč naboj

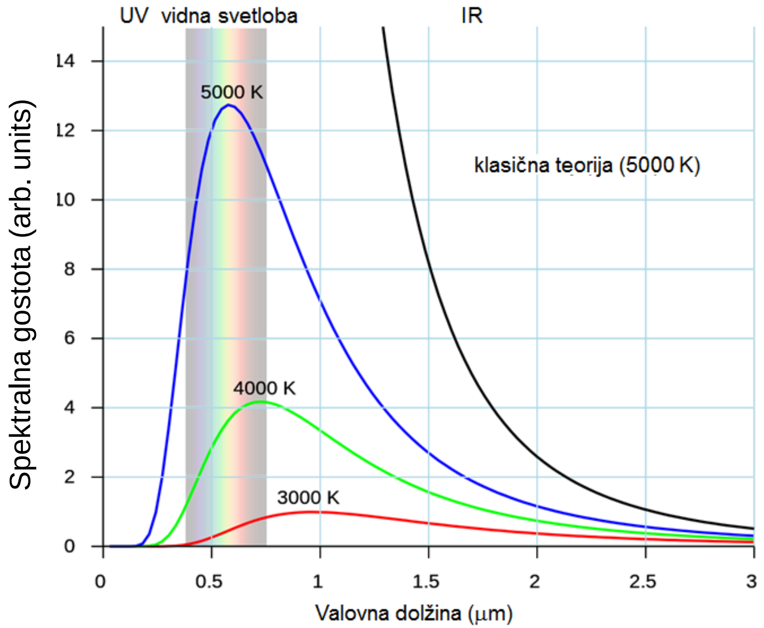


Heinrich Hertz



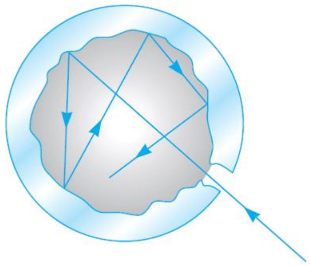
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

- Sevanje črnega telesa:



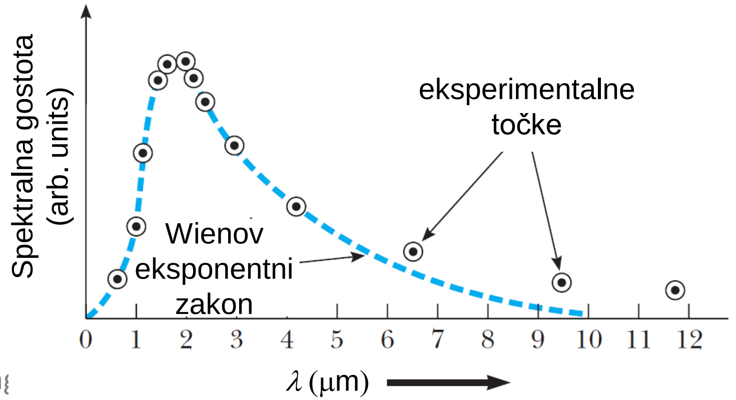
The Nobel Prize in Physics 1911

Wilhelm Wien
Prize share: 1/1



The Nobel Prize in Physics 1911 was awarded to Wilhelm Wien *"for his discoveries regarding the laws governing the radiation of heat".*

- Stefanov zakon (l. 1879): $j = \sigma T^4$
- Wienov zakon (l. 1893): $\lambda_{max} T = 2.898 \times 10^{-3}\ \mathrm{m \cdot K}$
- Wienov eksponentni zakon: $\frac{\mathrm{d}j}{\mathrm{d}\nu} \propto \nu^3 \mathrm{e}^{-\beta\nu/T}$

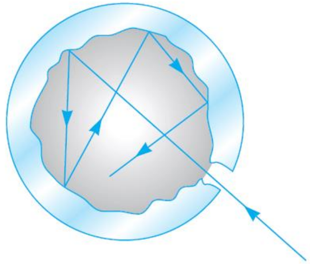


SIMULACIJA

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning

3.2 Svetloba – valovanje ali delci?

- Sevanje črnega telesa (l. 1900): kvantizacija E nivojev

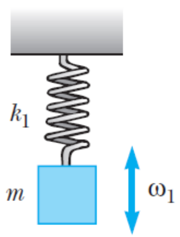


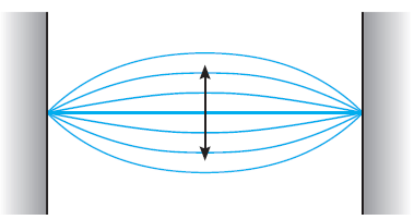
$$\mathrm{d}j = \frac{c}{4}\frac{\mathrm{d}E}{V} = \frac{c}{4}\overline{E}\frac{8\pi\nu^2}{c^3}\mathrm{d}\nu$$

Rayleight-Jeans: vs. Planck:

Rayleight-Jeans:

- EM valovi
- $\overline{E} = k_B T$
- $\frac{\mathrm{d}j}{\mathrm{d}\nu} = \frac{2\pi\nu^2}{c^2}k_B T$





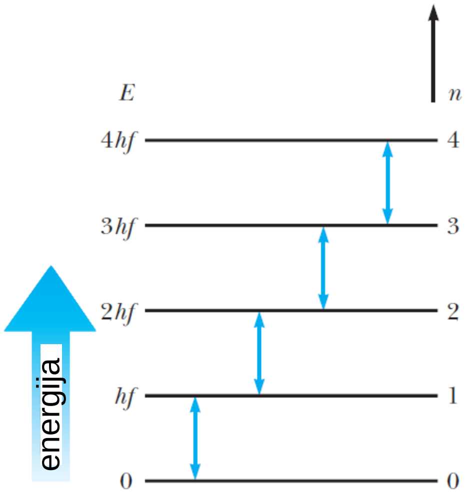
The Nobel Prize in Physics 1918

Max Karl Ernst Ludwig Planck
Prize share: 1/1

The Nobel Prize in Physics 1918 was awarded to Max Planck *"in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta".*

Planck:

- oscilacije naboja v stenah
- $\overline{E} = \frac{h\nu}{e^{h\nu/k_B T} - 1}$
- $\frac{\mathrm{d}j}{\mathrm{d}\nu} = \frac{2\pi\nu^2}{c^2}\frac{h\nu}{e^{h\nu/k_B T} - 1}$



Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

3.2 Svetloba – valovanje ali delci?

➢ Einstein: Annus Mirabilis

Albert Einstein

adp annalen der physik

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Article

Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt

A. Einstein

Teorija kvantizacije svetlobe: fotoefekt
A. Einstein, Ann. Physik **322**, 132 (1905)

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Article

Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen

A. Einstein

Brownovo gibanje: realnost atomov
A. Einstein, Ann. Physik **322**, 549 (1905)

adp annalen der physik

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Article

Zur Elektrodynamik bewegter Körper

A. Einstein

Posebna teorija relativnosti:
A. Einstein, Ann. Physik **322**, 891 (1905)

adp annalen der physik

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Article

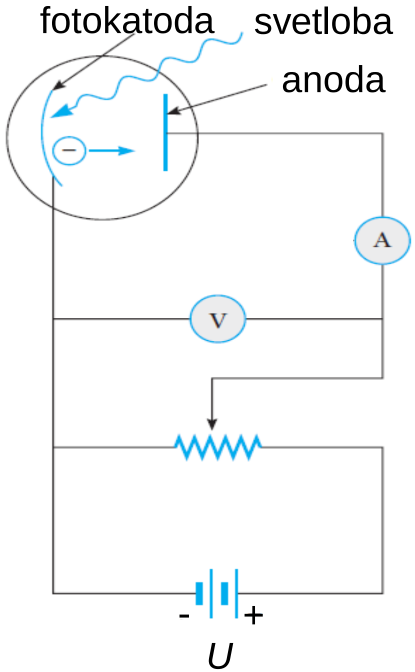
Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?

A. Einstein

Mirovna energija: $E = mc^2$
A. Einstein, Ann. Physik **323**, 639 (1905)

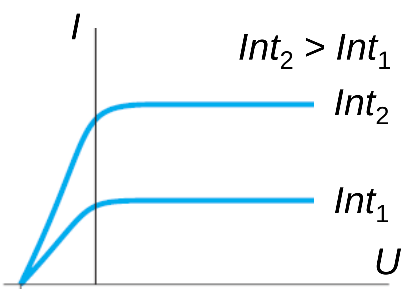
3.2 Svetloba – valovanje ali delci?

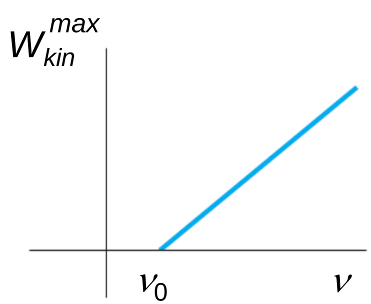
- Fotoefekt (l. 1905): kvantizacija svetlobe



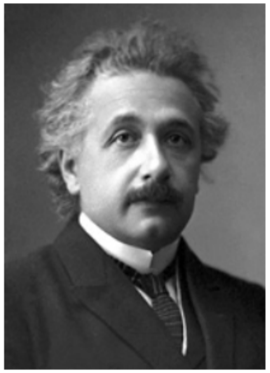
SIMULACIJA

$$W_{kin}^{max} = eU_z = h\nu - \phi$$



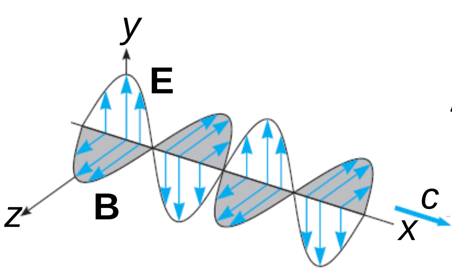


The Nobel Prize in Physics 1921



Albert Einstein
Prize share: 1/1

The Nobel Prize in Physics 1921 was awarded to Albert Einstein *"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect".*



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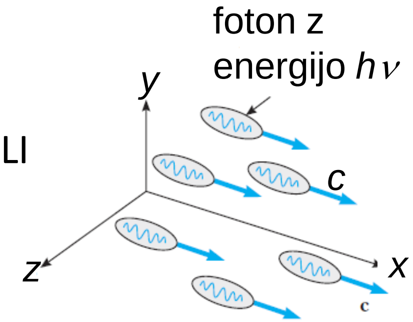


Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

3.2 Svetloba – valovanje ali delci?

- Comptonovo sipanje (l. 1923):

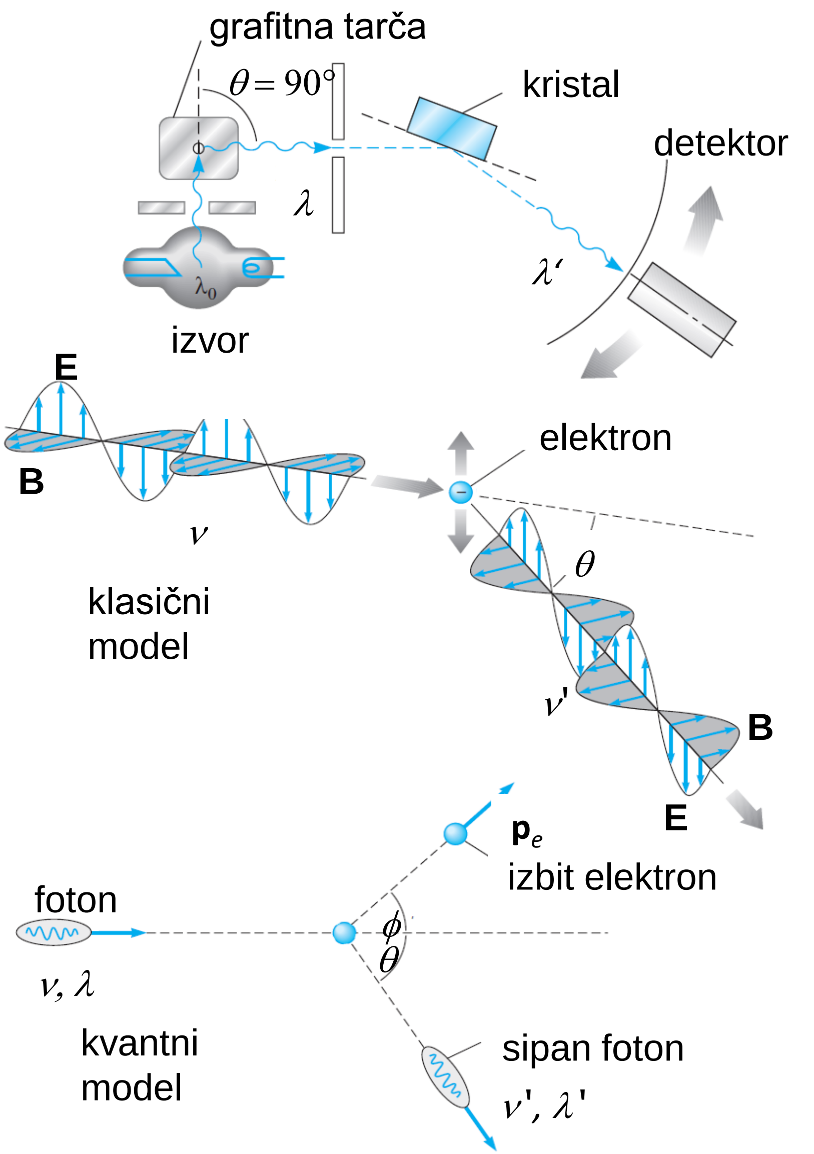
$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

The Nobel Prize in Physics 1927

Arthur Holly Compton
Prize share: 1/2

Charles Thomson Rees Wilson
Prize share: 1/2

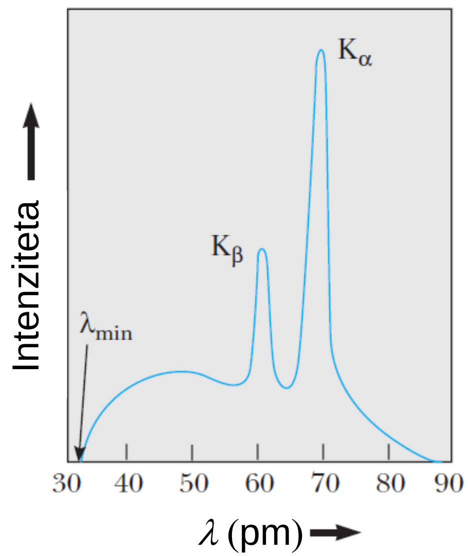
The Nobel Prize in Physics 1927 was divided equally between Arthur Holly Compton *"for his discovery of the effect named after him"* and Charles Thomson Rees Wilson *"for his method of making the paths of electrically charged particles visible by condensation of vapour"*.

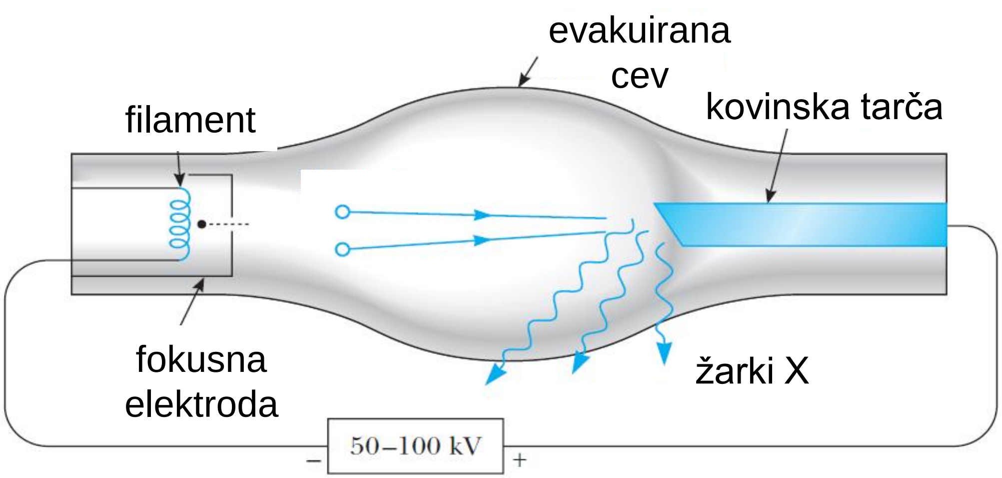


Vir: internet; Serway, povzeto po Moses & Moyer, Modern Physics, Thomson Learning, 2005

3.2 Svetloba – valovanje ali delci?

- Zavorno sevanje:





The Nobel Prize in Physics 1901

Wilhelm Conrad Röntgen
Prize share: 1/1

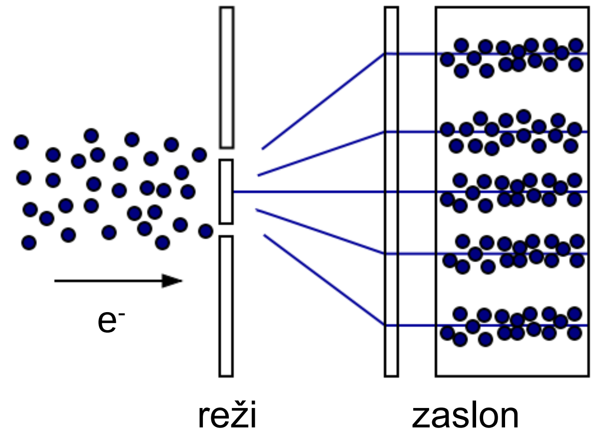
The Nobel Prize in Physics 1901 was awarded to Wilhelm Conrad Röntgen *"in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him".*

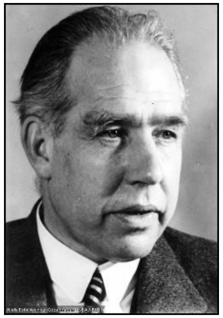
$$\lambda_{min} = \frac{hc}{eU}$$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

3.2 Svetloba – valovanje ali delci?

- Delčno-valovna komplementarnost:





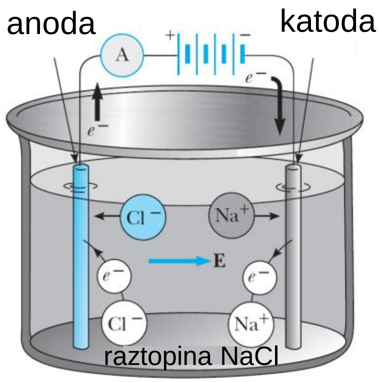
Niels Bohr

Every process can be interpreted either in terms of corpuscles or in terms of waves, but on the other hand it is beyond our power to produce proof that it is actually corpuscles or waves with which we are dealing, for we cannot simultaneously determine all the other properties which are distinctive of a corpuscle or of a wave, as the case may be.

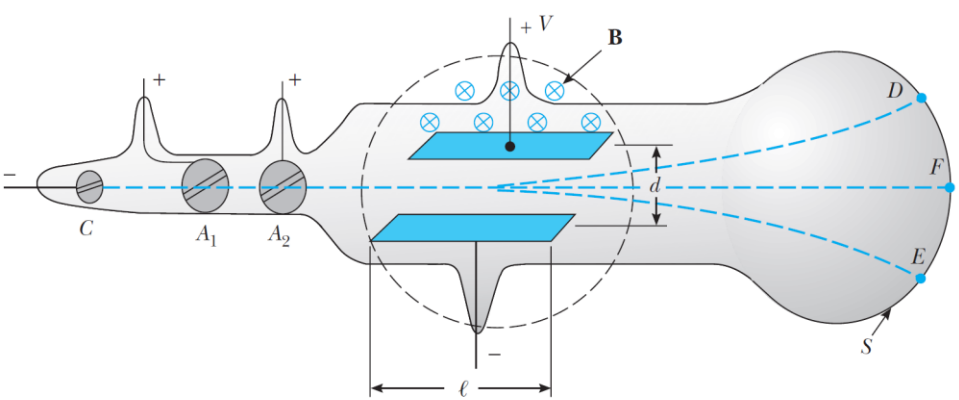
Vir: internet

3.3 Atomska struktura snovi in Bohrov model atoma

- M. Faraday (l. 1833): zakon elektrolize



- J. J. Thomson (l. 1897): odkritje elektrona (e/m)



The Nobel Prize in Physics 1906

Joseph John Thomson

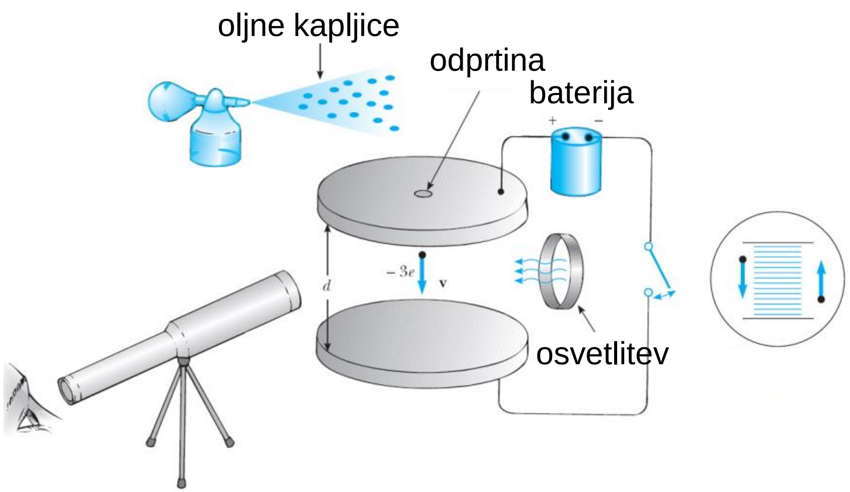
Prize share: 1/1

The Nobel Prize in Physics 1906 was awarded to J.J. Thomson *"in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases".*

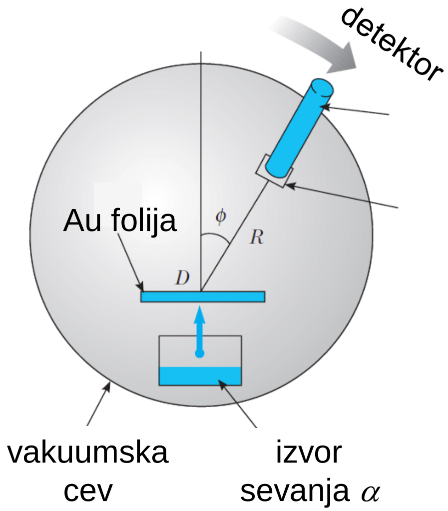
Vir: internet, povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

3.3 Atomska struktura snovi in Bohrov model atoma

- R. Millikan (l. 1909): določitev osnovnega naboja



- E. Rutherford (l. 1913): planetarni model atoma



SIMULACIJA

The Nobel Prize in Physics 1923

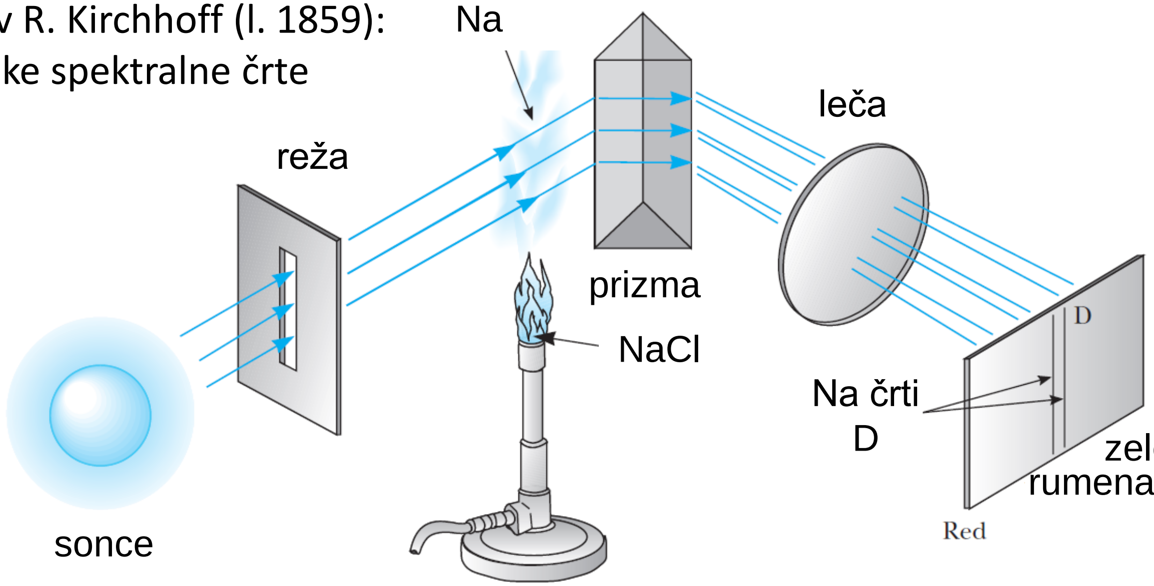
Robert Andrews Millikan
Prize share: 1/1

The Nobel Prize in Physics 1923 was awarded to Robert A. Millikan *"for his work on the elementary charge of electricity and on the photoelectric effect".*

Vir: internet povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

3.3 Atomska struktura snovi in Bohrov model atoma

- Gustav R. Kirchhoff (l. 1859): atomske spektralne črte

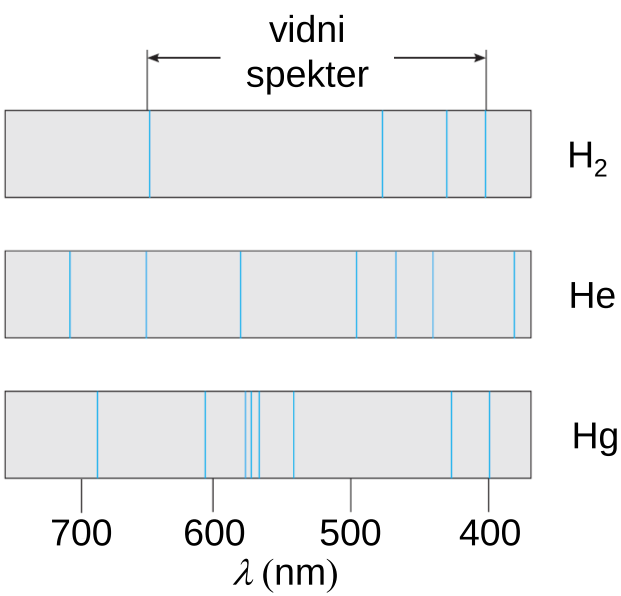


Gustav R. Kirchhoff

1. Balmerjeva serija: $\lambda = C_2 \dfrac{n^2}{n^2 - 2^2}$ $\quad n = 3, 4, 5, \ldots$

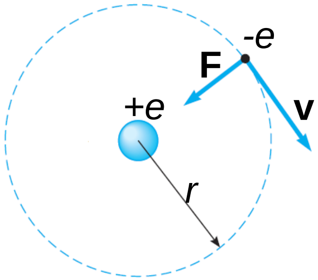
2. ostale serije: $\dfrac{1}{\lambda} = R\left(\dfrac{1}{n_f^2} - \dfrac{1}{n_i^2}\right)$

Lymanova serija (UV)	$n_f = 1$	$n_i = 2, 3, 4, \ldots$
Balmerjeva serija (VIS-UV)	$n_f = 2$	$n_i = 3, 4, 5, \ldots$
Paschenova serija (IR)	$n_f = 3$	$n_i = 4, 5, 6, \ldots$
Brackettova serija (IR)	$n_f = 4$	$n_i = 5, 6, 7, \ldots$
Pfundova serija (IR)	$n_f = 5$	$n_i = 6, 7, 8, \ldots$



Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

- Bohrov (kvantni) model atoma (l. 1913): $mvr_n = n\hbar,\ n = 1, 2, 3, \ldots$



kvantizacija vrtilne količine

kvantizacija energij

$$E_n = -\frac{1}{2}\frac{e^2}{4\pi\epsilon_0 r_B}\frac{Z^2}{n^2}$$

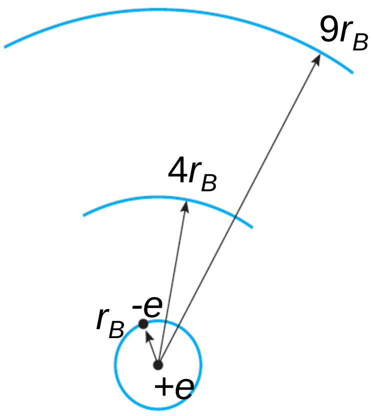
kvantizacija radijev

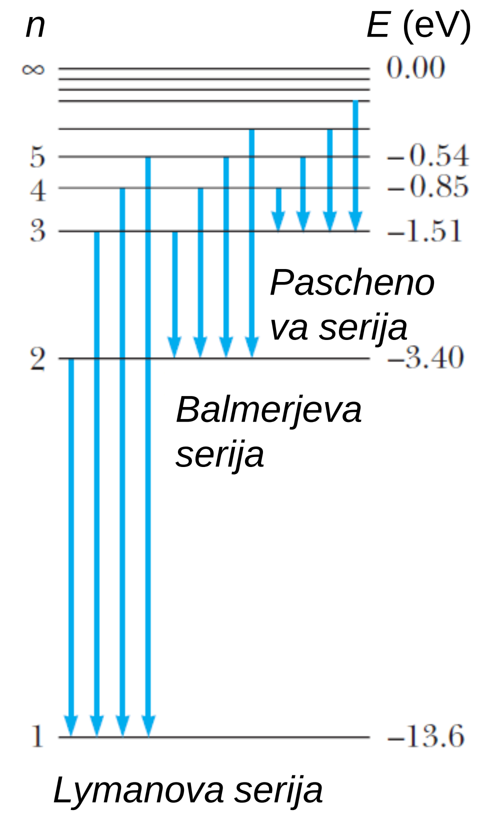
$$r_n = \frac{n^2}{Z} r_B,\ r_B = \frac{4\pi\epsilon_0\hbar^2}{me^2}$$

The Nobel Prize in Physics 1922

Niels Henrik David Bohr
Prize share: 1/1

The Nobel Prize in Physics 1922 was awarded to Niels Bohr *"for his services in the investigation of the structure of atoms and of the radiation emanating from them"*.





Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

Univerza *v Ljubljani*
Fakulteta za *matematiko in fiziko*

MODERNA FIZIKA

Kvantna mehanika 2
Kvantnomehanski opis

Andrej Zorko
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

4.1 Delčno-valovna dualnost materije

- de Brogliejevi valovi (l. 1923): materija kot valovanje

$$E = mc^2 = \sqrt{(cp)^2 + (m_0c^2)^2}$$

relativnost

za foton $m_0 = 0$

$$p = \frac{E}{c}$$

$$E = h\nu = \frac{hc}{\lambda}$$

fotoefekt

$$\frac{h}{\lambda} = \frac{E}{c}$$

$$\lambda = \frac{h}{p}$$

de Brogliejeva hipoteza

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

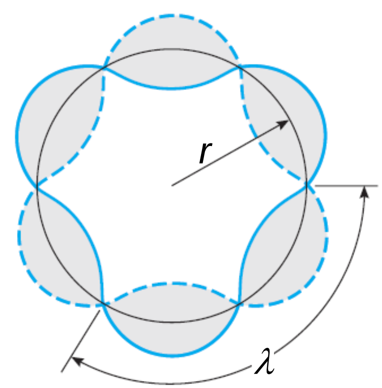
za masivni delec?

The Nobel Prize in Physics 1929

Prince Louis-Victor Pierre Raymond de Broglie
Prize share: 1/1

The Nobel Prize in Physics 1929 was awarded to Louis de Broglie *"for his discovery of the wave nature of electrons"*.

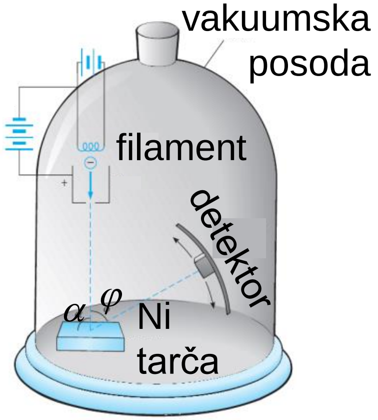
- Konstruktivna interferenca valov
- Kvantizacija vrtilne količine v atomu

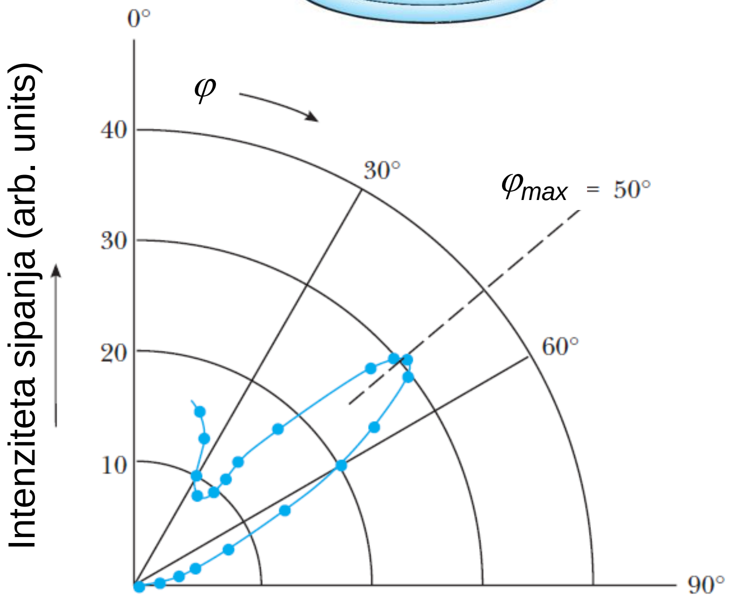


Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

4.1 Delčno-valovna dualnost materije

- Eksperiment Davisonna in Germerja (l. 1927):





- Načelo komplementarnosti

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

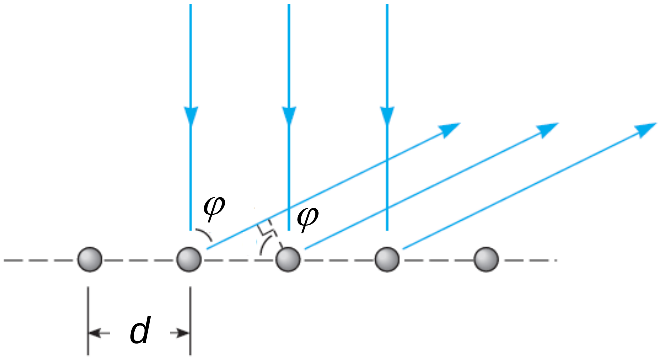
The Nobel Prize in Physics 1937

Clinton Joseph Davisson
Prize share: 1/2

George Paget Thomson
Prize share: 1/2

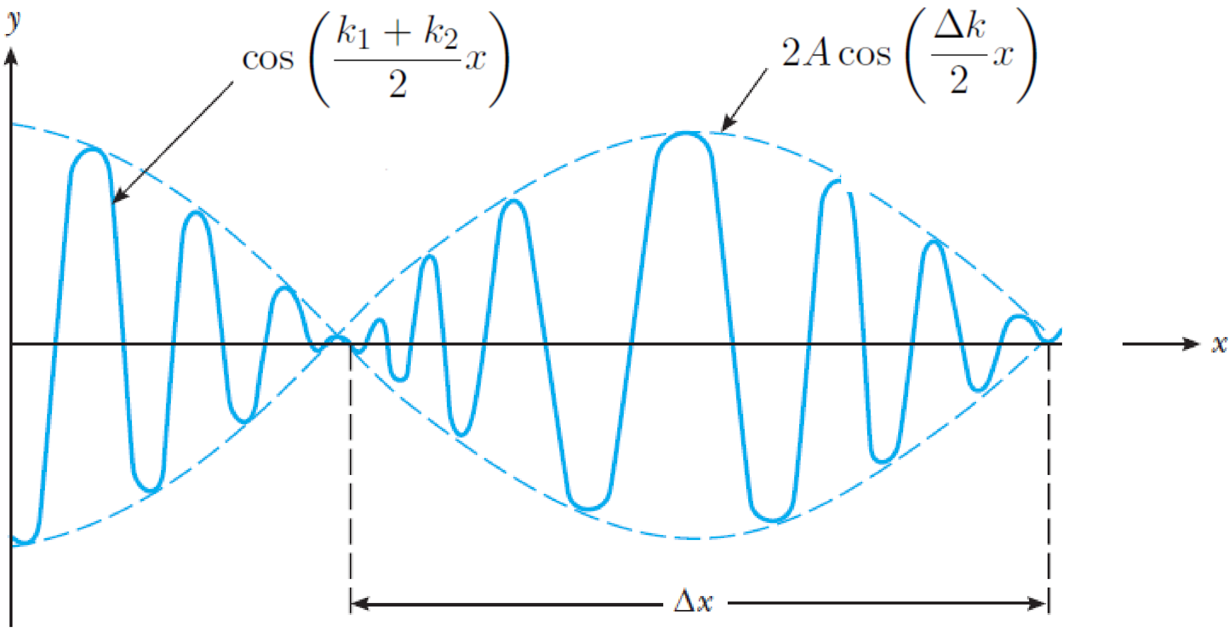
The Nobel Prize in Physics 1937 was awarded jointly to Clinton Joseph Davisson and George Paget Thomson *"for their experimental discovery of the diffraction of electrons by crystals"*

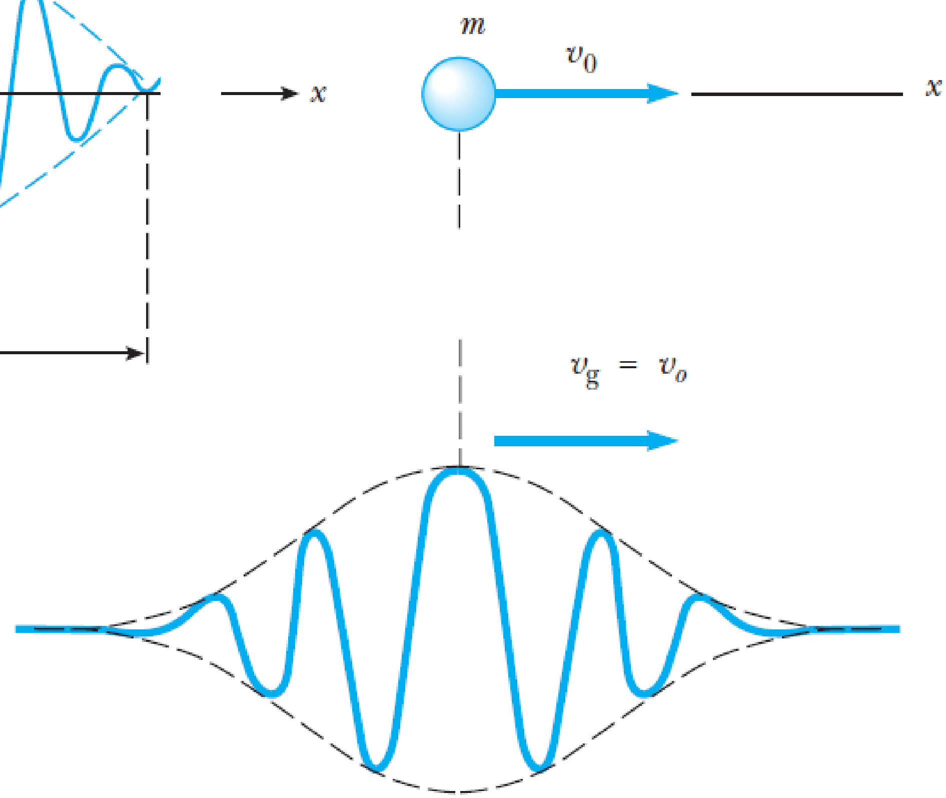
$$d \sin \varphi = n\lambda$$



4.2 Valovni paket

- Superpozicija ravnih valov:





$$f(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} a(k) e^{ikx} dx$$

SIMULACIJA

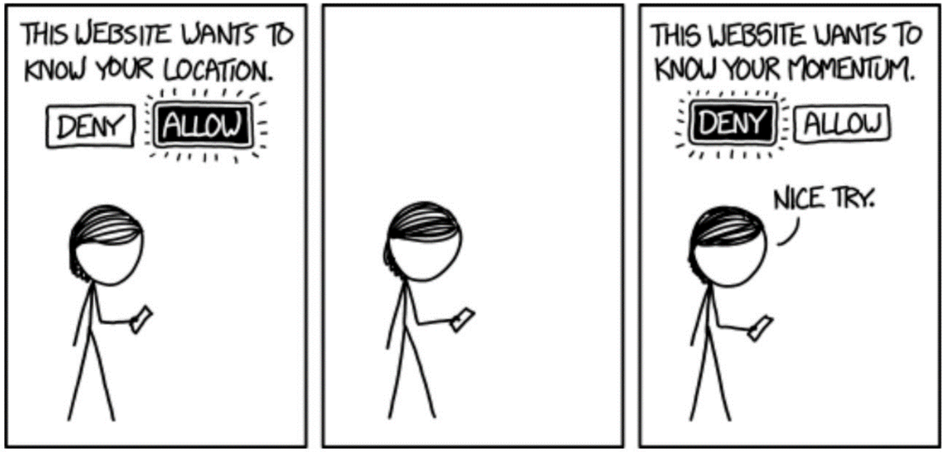
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

4.3 Heisenbergovo načelo nedoločenosti

- Nedoločenost lege in gibalne količine (l. 1927):

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$



The Nobel Prize in Physics 1932

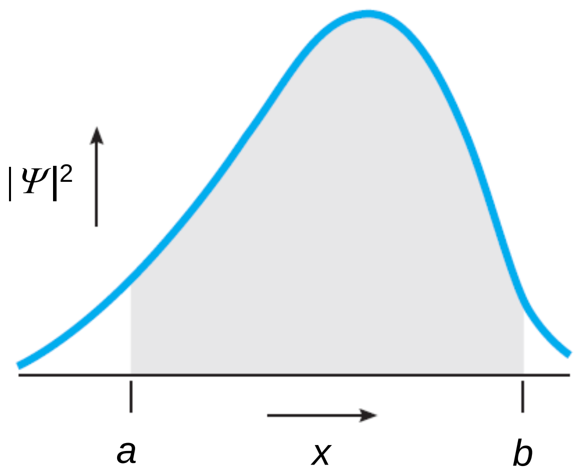
Werner Karl Heisenberg
Prize share: 1/1

The Nobel Prize in Physics 1932 was awarded to Werner Heisenberg *"for the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen"*.

Vir: internet

4.4 Valovna funkcija

- Bornova interpretacija valovne funkcije (l. 1925):



$$P(x)\mathrm{d}x = |\Psi(x,\,t)|^2\mathrm{d}x \qquad P = \int_a^b |\Psi(x,\,t)|^2\mathrm{d}x$$

$$\int_{-\infty}^{\infty} |\Psi(x,\,t)|^2\mathrm{d}x = 1$$

The Nobel Prize in Physics 1954

Max Born
Prize share: 1/2

Walther Bothe
Prize share: 1/2

The Nobel Prize in Physics 1954 was divided equally between Max Born *"for his fundamental research in quantum mechanics, especially for his statistical interpretation of the wavefunction"* and Walther Bothe *"for the coincidence method and his discoveries made therewith"*.

- Gibanje prostega delca – RAVNI VAL

$$\Psi_k(x,\,t) = A\mathrm{e}^{i(kx-\omega t)} = A\left[\cos(kx-\omega t) + i\sin(kx-\omega t)\right]$$

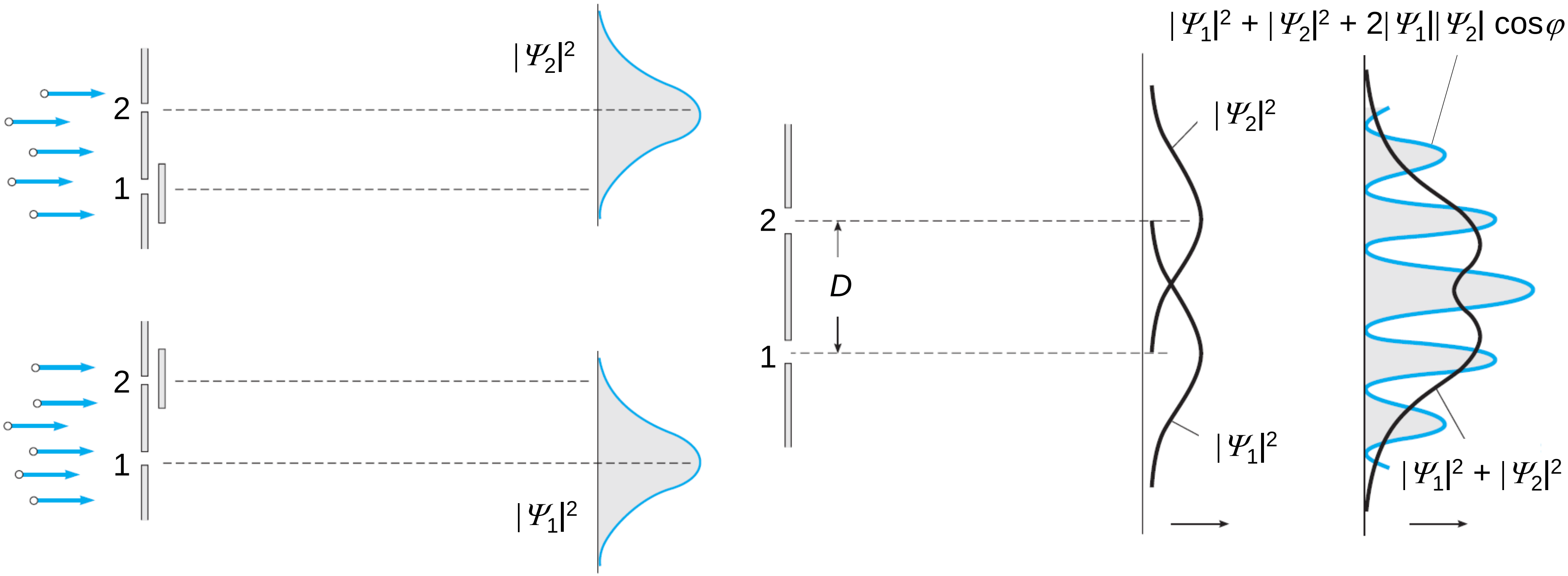
$$k = \frac{p}{\hbar} \qquad \omega = \frac{E}{\hbar}$$

$$|\Psi_k(x,\,t)|^2 = |A|^2$$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

4.4 Valovna funkcija

- Sipanje delcev (elektronov) na dveh režah:



Primer	Valovna funkcija	Meritve na zaslonu
Izmerimo, da gre elektron skozi režo 1 ali režo 2:	Ψ_1 ali Ψ_2	$\lvert\Psi_1\rvert^2 + \lvert\Psi_2\rvert^2$
Meritev, skozi katero režo gre elektron, ni izvedena:	$\Psi_1 + \Psi_2$	$\lvert\Psi_1\rvert^2 + \lvert\Psi_2\rvert^2 + 2\lvert\Psi_1\rvert\lvert\Psi_2\rvert \cos\varphi$

SIMULACIJA

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

4.5 Schrödingerjeva enačba

- Valovna enačba v KM (l. 1926): :

$$-\frac{\hbar^2}{2m}\frac{\partial^2\Psi(x,t)}{\partial x^2}+U(x)\Psi(x,t)=i\hbar\frac{\partial\Psi(x,t)}{\partial t}$$

- Stacionarna stanja: $\Psi(x,t)=\psi(x)\phi(t)$

$$-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2\psi(x)}{\mathrm{d}x^2}\frac{1}{\psi(x)}+U(x)=i\hbar\frac{\mathrm{d}\phi(t)}{\mathrm{d}t}\frac{1}{\phi(t)}$$

$$i\hbar\frac{\mathrm{d}\phi(t)}{\mathrm{d}t}=E\phi(t)$$

$$\phi(t)=\mathrm{e}^{-iEt/\hbar}=\mathrm{e}^{-i\omega t}$$

$$-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2\psi(x)}{\mathrm{d}x^2}+U(x)\psi(x)=E\psi(x)$$

The Nobel Prize in Physics 1933

Erwin Schrödinger
Prize share: 1/2

Paul Adrien Maurice Dirac
Prize share: 1/2

The Nobel Prize in Physics 1933 was awarded jointly to Erwin Schrödinger and Paul Adrien Maurice Dirac *"for the discovery of new productive forms of atomic theory"*

SIMULACIJA

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

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MODERNA FIZIKA

Kvantna mehanika 3

Gibanje v 1D

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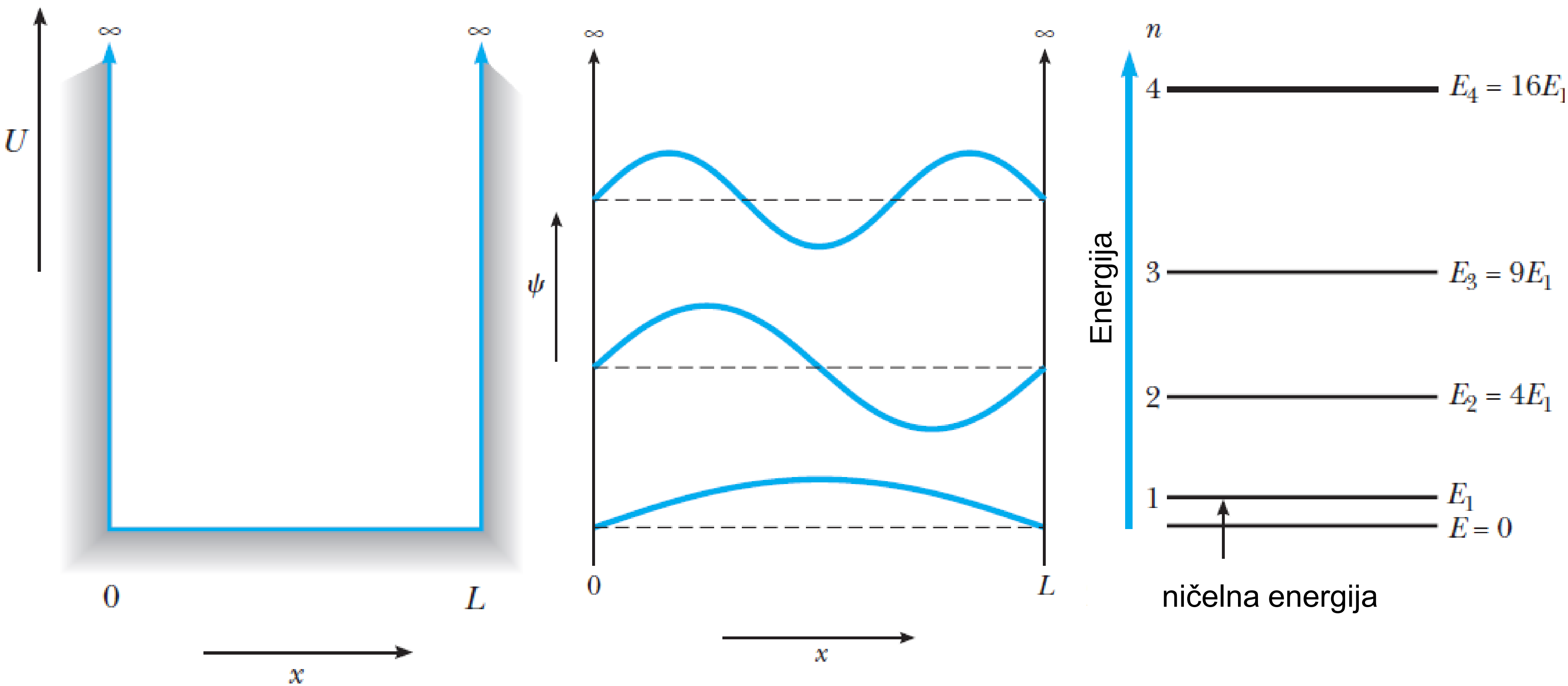
5.1 Delec v neskončni potencialni jami

- Stacionarna Schrödingerjeva enačba:

$$\frac{\mathrm{d}^2\psi(x)}{\mathrm{d}x^2} = -\frac{2mE}{\hbar^2}\psi(x) = -k^2\psi(x)$$

$$\psi_n = \sqrt{\frac{2}{L}}\sin\left(\frac{n\pi}{L}x\right) \qquad E_n = \frac{\hbar^2 k_n^2}{2m} = \frac{\hbar^2\pi 2}{2mL^2}n^2$$

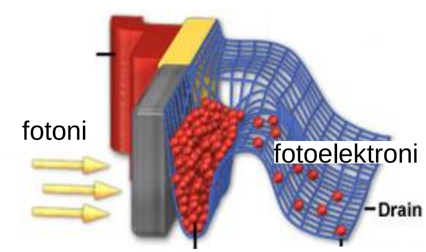


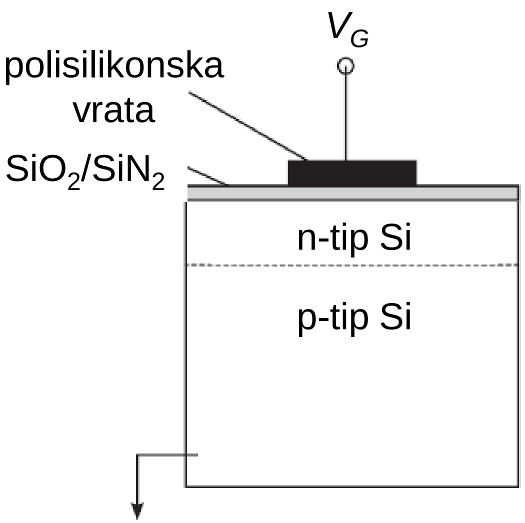
SIMULACIJA

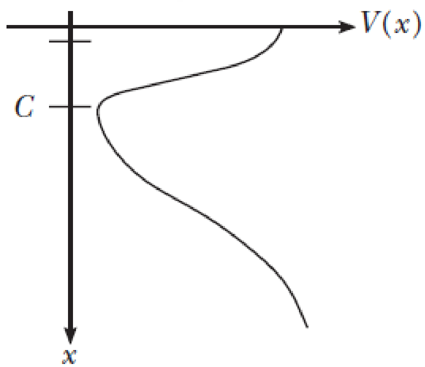
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

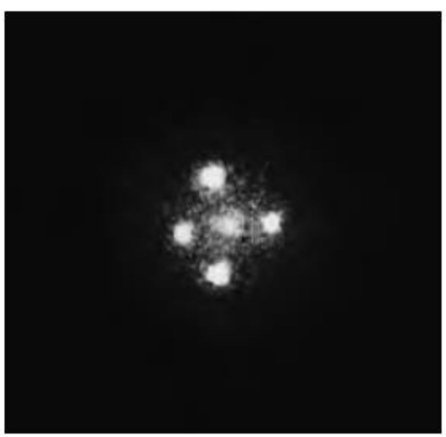
5.1 Delec v neskončni potencialni jami

- CCD detektor fotonov:









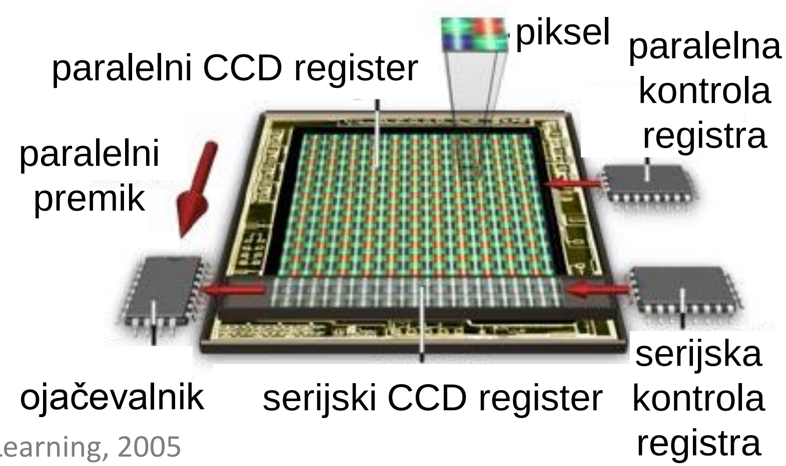
Hubblov teleskop

foto-elektronika

The Nobel Prize in Physics 2009

Photo: U. Montan	Photo: U. Montan	Photo: U. Montan
Charles Kuen Kao	**Willard S. Boyle**	**George E. Smith**
Prize share: 1/2	**Prize share:** 1/4	**Prize share:** 1/4

The Nobel Prize in Physics 2009 was divided, one half awarded to Charles Kuen Kao *"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"*, the other half jointly to Willard S. Boyle and George E. Smith *"for the invention of an imaging semiconductor circuit - the CCD sensor"*.

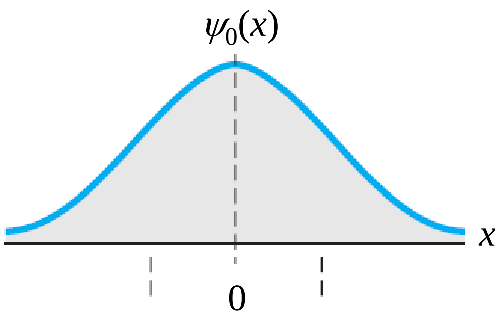


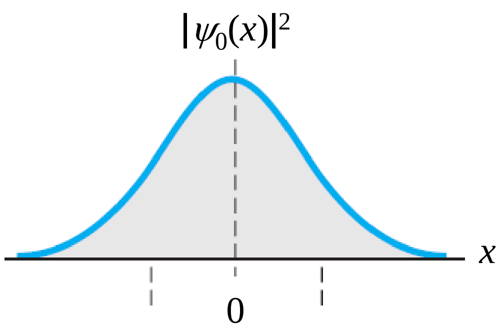
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

5.2 Kvantni harmonski oscilator

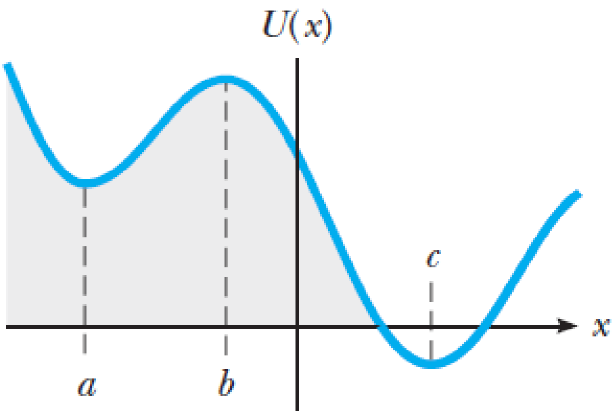
- Osnovno stanje:

$$\frac{\mathrm{d}^2\psi(x)}{\mathrm{d}x^2} = \frac{2m}{\hbar^2}\left(\frac{1}{2}m\omega^2x^2 - E\right)\psi(x)$$





$$\psi_0 = \sqrt[4]{\frac{m\omega}{\hbar\pi}}\exp\left(-\frac{m\omega}{2\hbar}x^2\right)$$



stabilno nestabilno stabilno

$$U(x) = U(c) + \frac{1}{2}K(x-c)^2$$
$$= U(c) + \frac{1}{2}m\omega^2(x-c)^2$$

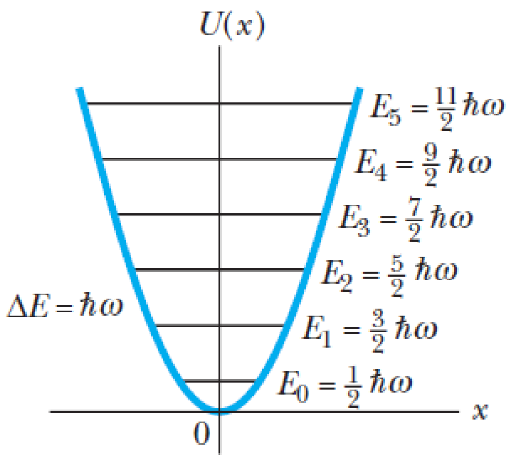
Vir: Serway, povzeto po Moses & Moyer, Modern Physics, Thomson Learning, 2005

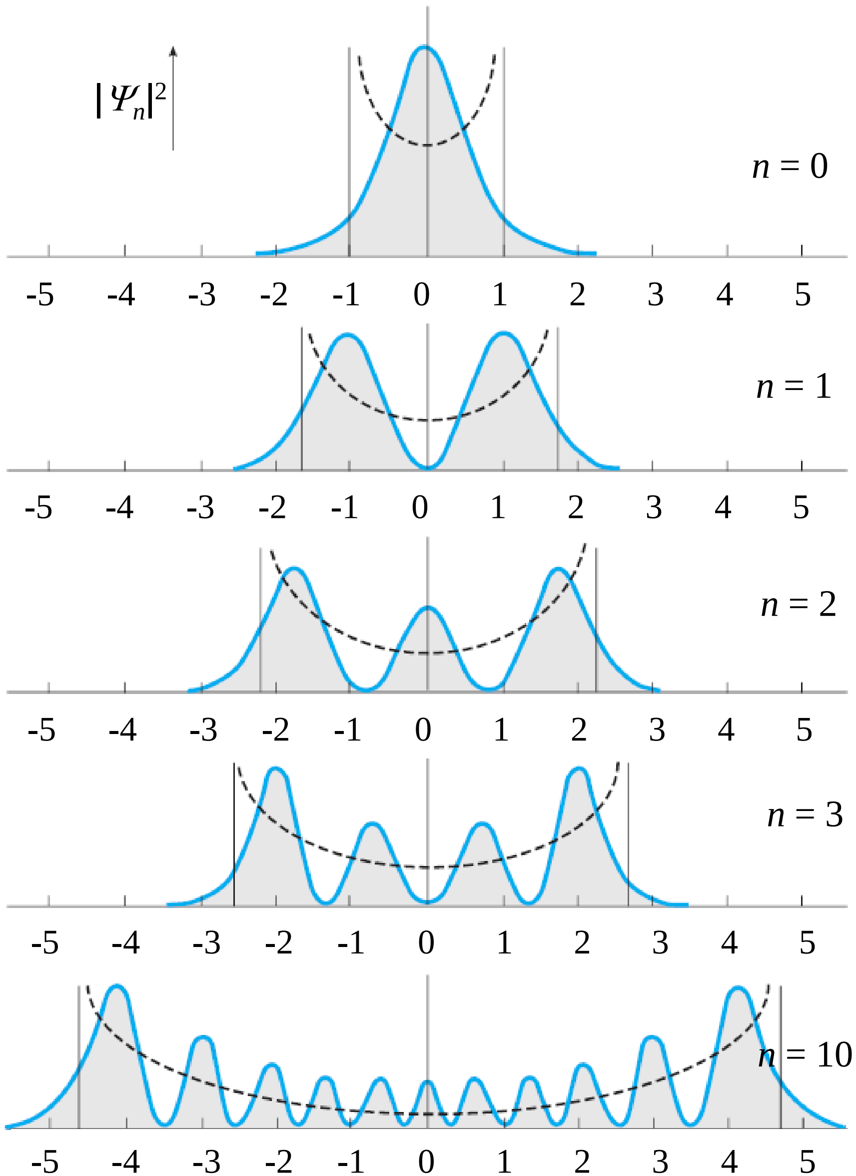
5.2 Kvantni harmonski oscilator

- Vzbujena stanja:

$$\psi_n = \sqrt[4]{\frac{m\omega}{\hbar\pi}}\frac{1}{\sqrt{2^n n!}}\exp\left(-\frac{m\omega}{2\hbar}x^2\right)H_n\left(\sqrt{\frac{m\omega}{\hbar}}x\right)$$

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





SIMULACIJA

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

5.3 Povprečne vrednosti opazljivk in operatorji

- Povprečna lega: $$\langle x\rangle = \int_{-\infty}^{\infty} x\,|\Psi(x,\,t)|^2\,\mathrm{d}x$$

- Povprečje funkcije *f*(*x*): $$\langle f(x)\rangle = \int_{-\infty}^{\infty} f(x)\,|\Psi(x,\,t)|^2\,\mathrm{d}x$$

- Povprečna gibalna količina: $$\langle p\rangle = m\frac{\mathrm{d}\langle x\rangle}{\mathrm{d}t}\int_{-\infty}^{\infty}\Psi^*(x,\,t)\left(-i\hbar\frac{\partial}{\partial x}\right)\Psi(x,\,t)\,\mathrm{d}x$$

- Opazljivka: Q
- Operator: $\hat{Q}$

$$\langle Q\rangle = \int_{-\infty}^{\infty}\Psi^*(x,\,t)\,\hat{Q}\,\Psi(x,\,t)\,\mathrm{d}x$$

Opazljivka	Simbol	Operator
Lega	*x*	x
Gibalna količina	*p*	$-i\hbar\frac{\partial}{\partial x}$
Potencialna energija	*U*	$U(x)$
Kinetična energija	W_{kin}	$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}$
Hamiltonka	*H*	$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}+U(x)$
Polna energija	*E*	$i\hbar\frac{\partial}{\partial t}$

5.4 Razvoj valovnih funkcij

- Razvoj po bazi ortonormiranih lastnih funkcij: $\int_{-\infty}^{\infty} \psi_m^*(x)\psi_n(x)\mathrm{d}x = \delta_{m,\,n}$

$$c_n = \int_{-\infty}^{\infty} \psi_n^*(x)\Psi(x,\,t=0)\mathrm{d}x$$

$$\Psi(x,\,t=0) = \sum_n c_n \psi_n(x)$$

$$\sum_n |c_n|^2 = 1$$

SIMULACIJA

- Časovni razvoj:

$$\Psi(x,\,t) = \sum_n c_n \psi_n(x)\,\mathrm{e}^{-i\frac{E_n}{\hbar}t}$$

$$P(x,\,t) = \Psi^*(x,\,t)\Psi(x,\,t)$$
$$= \sum_n |c_n|^2|\psi_n(x)|^2 + \sum_{m,\,n} c_m^* c_n \psi_m^*(x)\psi_n(x)\,\mathrm{e}^{i\frac{E_m-E_n}{\hbar}t}$$

SIMULACIJA

- Povprečna vrednost energije:

$$\langle E\rangle = \int_{-\infty}^{\infty} \Psi^*(x,\,t)\hat{H}\Psi(x,\,t)\mathrm{d}x = \sum_n |c_n|^2 E_n$$

- Kolaps valovne funkcije:

SIMULACIJA

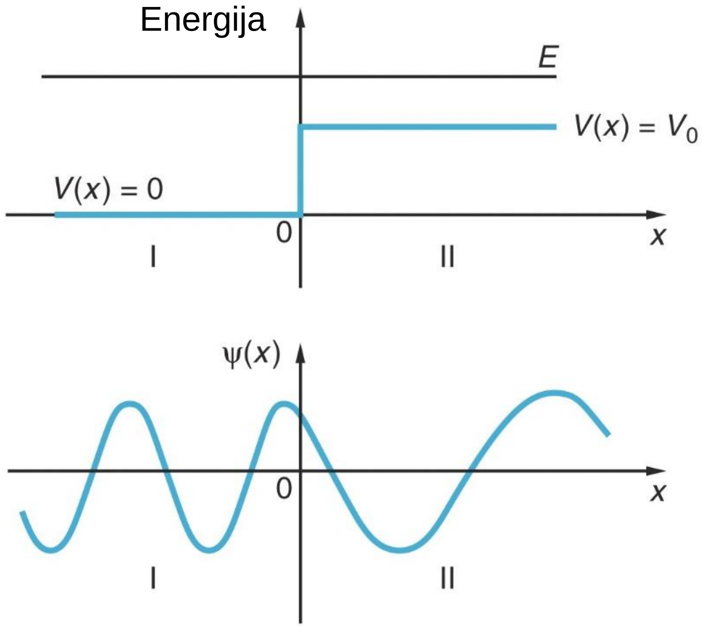
Vir: internet

- Operator gostote toka delcev: $$\hat{j} = -\frac{i\hbar}{2m}\left(\Psi^*\frac{\mathrm{d}\Psi}{\mathrm{d}x} - \frac{\mathrm{d}\Psi^*}{\mathrm{d}x}\Psi\right)$$
- ODBOJNOST: $$R = \left|\frac{k_1 - k_2}{k_1 + k_2}\right|^2$$
- PREPUSTNOST: $$T = \frac{4k_1k_2}{|k_1 + k_2|^2}$$

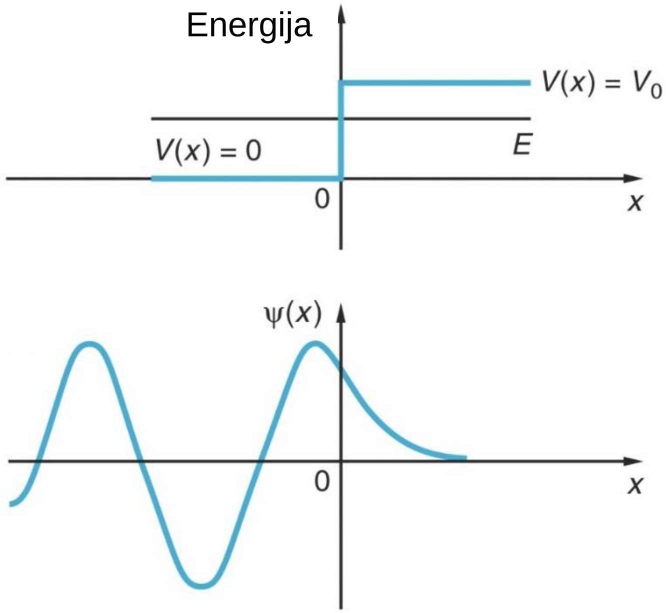
$$k_1 = \frac{\sqrt{2mE}}{\hbar}$$

$$k_2 = \frac{\sqrt{2m(E - V_0)}}{\hbar}$$

$E > V_0$



$E < V_0$: $R = 1$



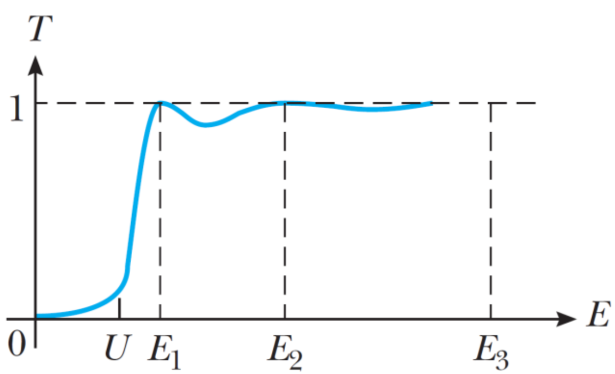
SIMULACIJA

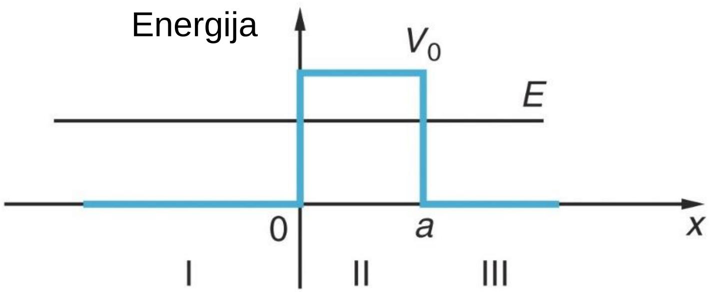
Vir: internet; povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

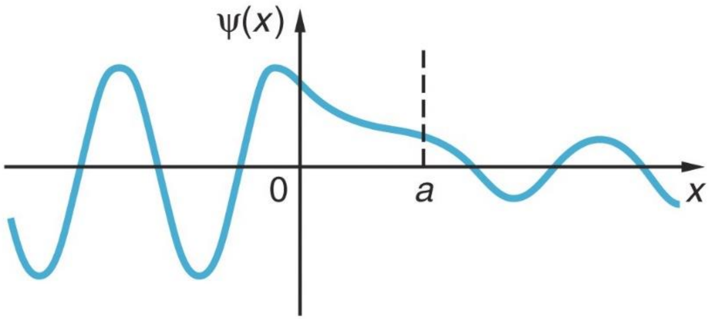
5.6 Potencialna plast

- ODBOJNOST: $$R = \frac{\left(\frac{k_2}{2k_1} - \frac{k_1}{2k_2}\right)^2 \sin^2(k_2 L)}{1 + \left(\frac{k_2}{2k_1} - \frac{k_1}{2k_2}\right)^2 \sin^2(k_2 L)}$$ $$k_1 = \frac{\sqrt{2mE}}{\hbar}$$
- PREPUSTNOST: $$T = \frac{1}{1 + \left(\frac{k_2}{2k_1} - \frac{k_1}{2k_2}\right)^2 \sin^2(k_2 L)}$$ $$k_2 = \frac{\sqrt{2m(E - V_0)}}{\hbar}$$
- TUNELIRANJE: $E < V_0$: $R \neq 1$

$$T = \frac{1}{1 + \left(\frac{\kappa}{2k_1} + \frac{k_1}{2\kappa}\right)^2 \sinh^2(\kappa L)} \qquad \kappa = \frac{\sqrt{2m(V_0 - E)}}{\hbar}$$







SIMULACIJA

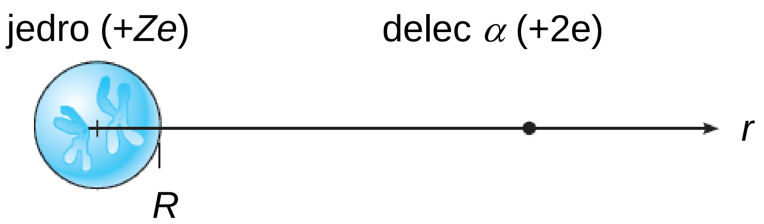
Vir: internet; povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

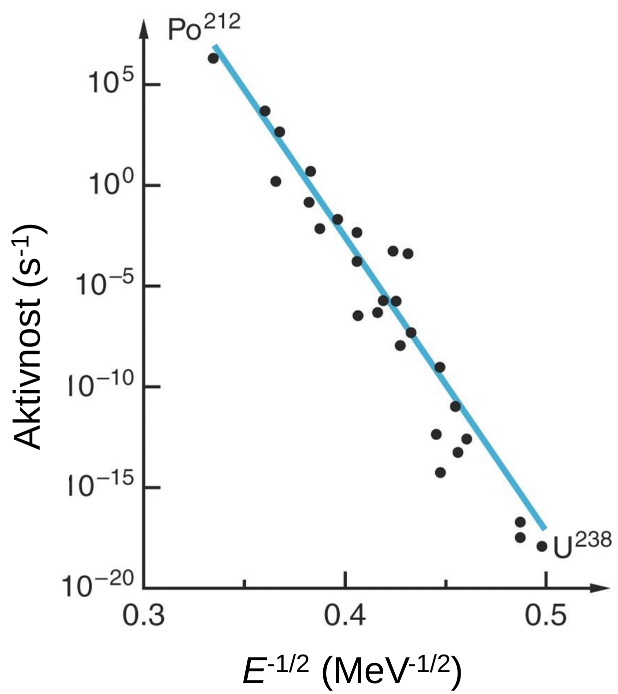
5.6 Potencialna plast

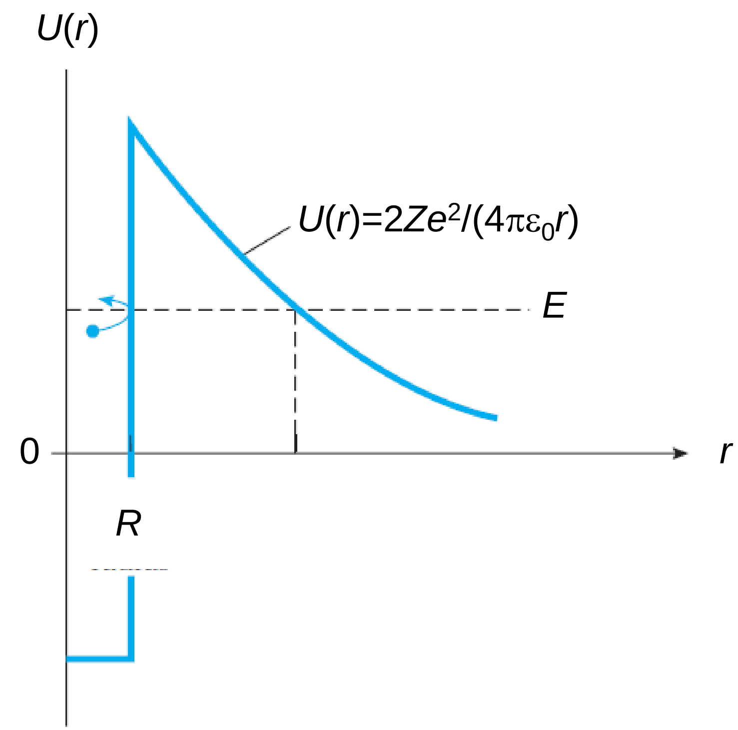
- Primeri tuneliranja:

1. RAZPAD α: $T(E) = \exp\left(-4\pi Z\sqrt{\frac{E_0}{E}} + 8\sqrt{\frac{8R}{r_0}}\right)$

$$r_0 = \frac{4\pi\epsilon_0\hbar^2}{m_\alpha e^2} \qquad E_0 = \frac{e^2}{8\pi\epsilon_0 r_0}$$



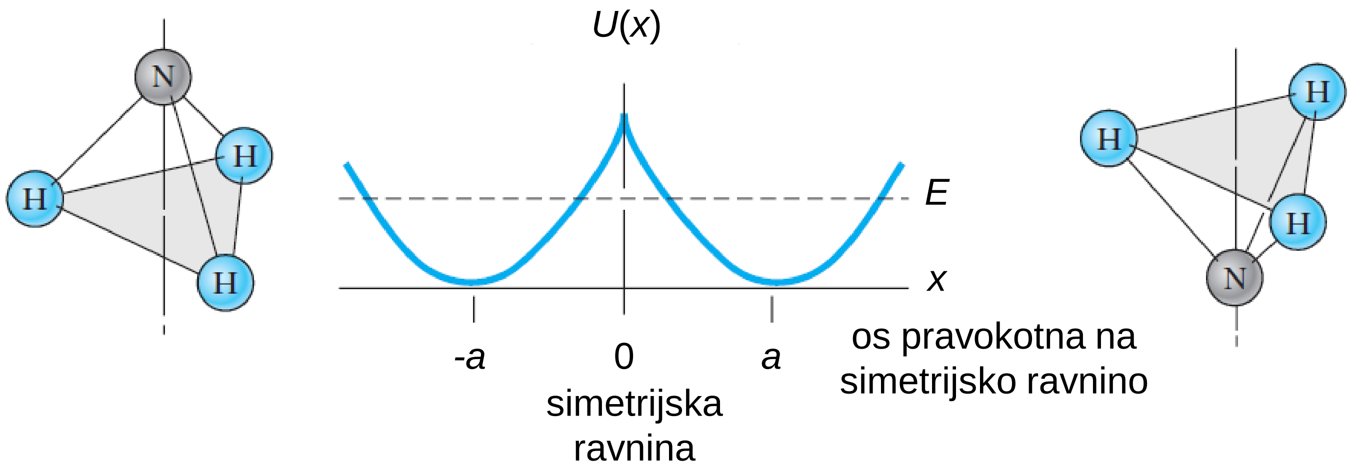




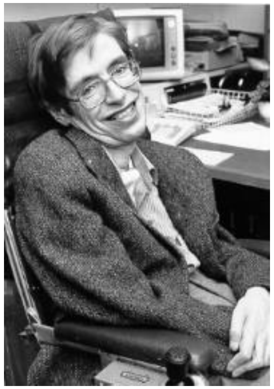
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

5.6 Potencialna plast

2. INVERZIJA NH_3 (amonijev maser):



3. SEVANJE črnih lukenj:

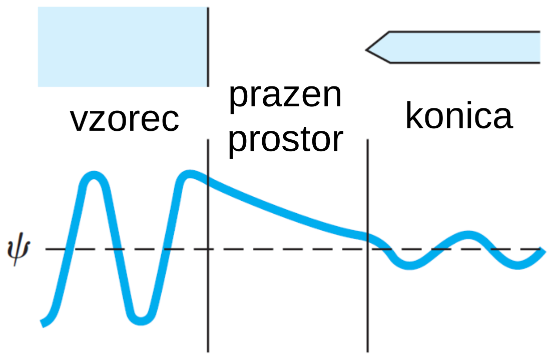


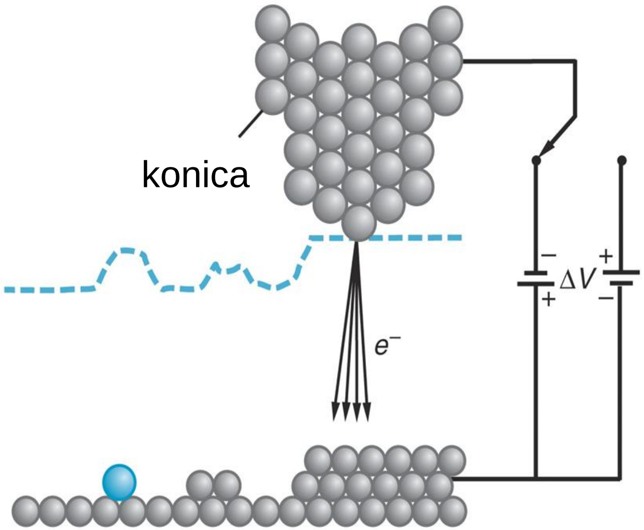
Stephen Hawking

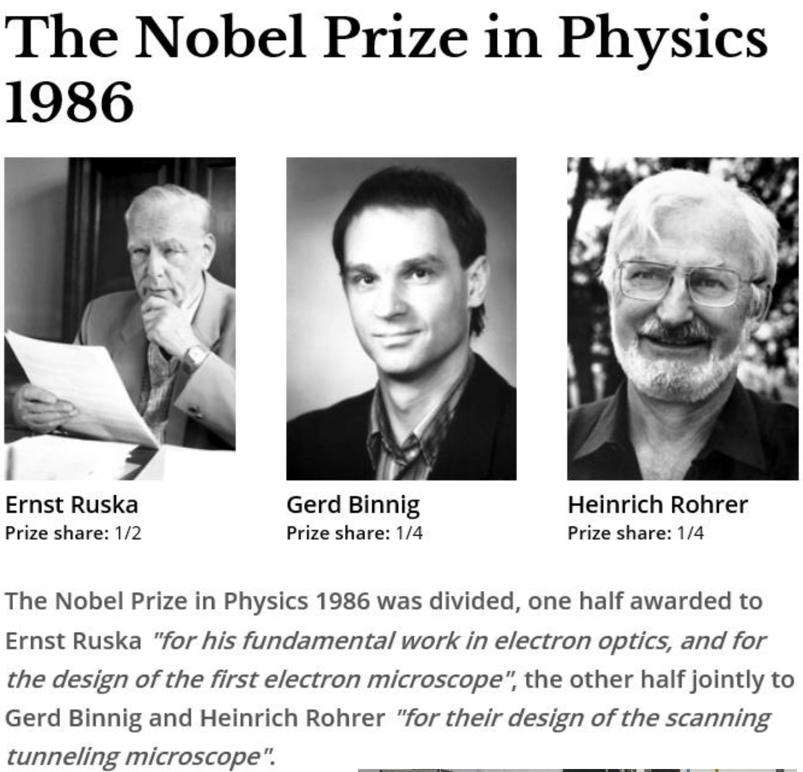
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

5.6 Potencialna plast

4. Vrstični tunelski mikroskop (STM):







STM (IJS)

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

Univerza v Ljubljani
Fakulteta za matematiko in fiziko

MODERNA FIZIKA

Kvantna mehanika 4
Gibanje v 3D

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6.1 Centralne sile

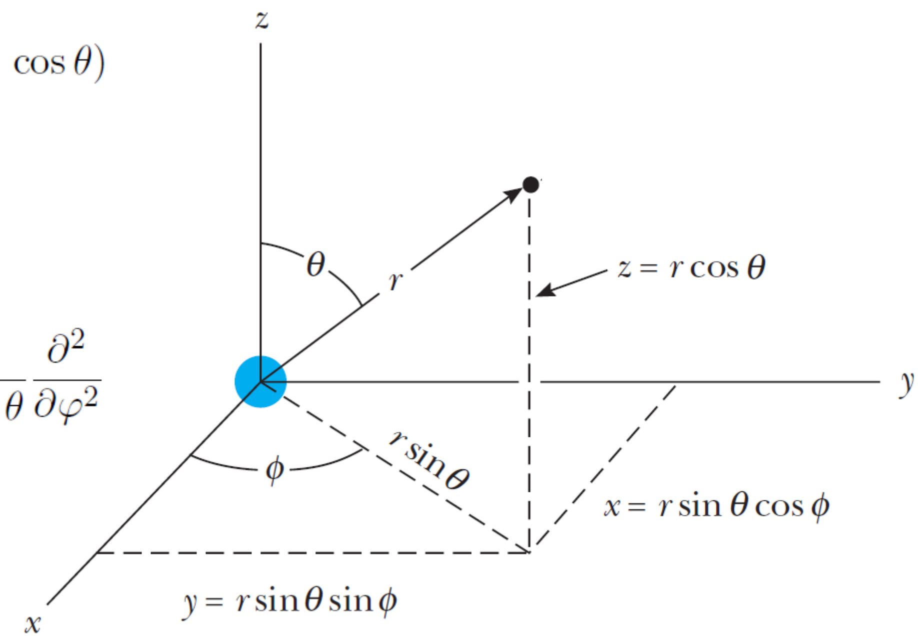
- Verjetnost: $$P\mathrm{d}V = |\Psi(\vec{r},\, t)|^2 \mathrm{d}V$$
- Stacionarna stanja: $$\Psi(\vec{r},\, t) = \psi(\vec{r})\mathrm{e}^{iEt/\hbar} = \psi(\vec{r})\mathrm{e}^{i\omega t}$$
- Hamiltonka: $$\hat{W}_{kin} = -\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) = -\frac{\hbar^2}{2m}\nabla^2$$

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\vec{r}) + U(\vec{r})\psi(\vec{r}) = E\psi(\vec{r})$$

- Krogelne koordinate: $\vec{r} = r(\sin\theta\cos\varphi,\ \sin\theta\sin\varphi,\ \cos\theta)$

$$\mathrm{d}V = r^2\mathrm{d}r\,\sin\theta\mathrm{d}\theta\mathrm{d}\varphi$$

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2} + \frac{1}{r^2\tan\theta}\frac{\partial}{\partial\theta} + \frac{1}{r^2\sin^2\theta}\frac{\partial^2}{\partial\varphi^2}$$



Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.1 Centralne sile

- Separacija spremenljivk: $$\psi(r) = R(r)\Theta(\theta)\Phi(\varphi)$$

- Azimutni del valovne funkcije: **magnetno kvantno število** ***m***

$$\frac{\mathrm{d}^2\Phi(\varphi)}{\mathrm{d}\varphi^2} = -m^2\Phi(\varphi) \qquad \Rightarrow \qquad \Phi(\varphi) = \mathrm{e}^{im\varphi}$$

- Polarni del valovne funkcije: **orbitalno kvantno število** ***l***

$$-\frac{\mathrm{d}^2\Theta(\theta)}{\mathrm{d}\theta^2} - \frac{1}{\tan\theta}\frac{\mathrm{d}\Theta(\theta)}{\mathrm{d}\theta} + \frac{m^2}{\sin\theta}\Theta(\theta) = l(l+1)\Theta(\theta)$$

$$\Rightarrow \quad \Theta(\theta) = P_l^m(\theta)$$

$$l = 0, 1, 2, ...$$
$$m = -l, -l+1, ..., l-1, l$$

Pridruženi Legendrovi polinomi $P_l^m(\theta)$

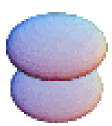
$$P_0^0 = 1$$
$$P_1^0 = 2\cos\theta$$
$$P_1^1 = \sin\theta$$
$$P_2^0 = 4(3\cos^2\theta - 1)$$
$$P_2^1 = 4\sin\theta\cos\theta$$
$$P_2^2 = \sin^2\theta$$

6.1 Centralne sile

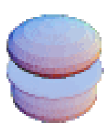
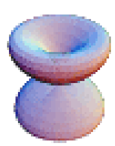
- Kotni del valovne funkcije: $\Theta(\theta)\Phi(\varphi) = Y_l^m(\theta,\phi) = A_m P_l^m(\theta)\mathrm{e}^{im\varphi}$

$|Y_0^0(\theta,\varphi)|^2$

$|Y_1^0(\theta,\varphi)|^2$ $|Y_1^1(\theta,\varphi)|^2$




$|Y_2^0(\theta,\varphi)|^2$ $|Y_2^1(\theta,\varphi)|^2$ $|Y_2^2(\theta,\varphi)|^2$


Krogelne funkcije $Y_l^m(\theta,\phi)$

$$Y_0^0 = \frac{1}{2\sqrt{\pi}}$$

$$Y_1^0 = \frac{1}{2}\sqrt{\frac{3}{\pi}}\cdot\cos\theta$$

$$Y_1^{\pm 1} = \mp\frac{1}{2}\sqrt{\frac{3}{2\pi}}\cdot\sin\theta\cdot e^{\pm i\phi}$$

$$Y_2^0 = \frac{1}{4}\sqrt{\frac{5}{\pi}}\cdot(3\cos^2\theta - 1)$$

$$Y_2^{\pm 1} = \mp\frac{1}{2}\sqrt{\frac{15}{2\pi}}\cdot\sin\theta\cdot\cos\theta\cdot e^{\pm i\phi}$$

$$Y_2^{\pm 2} = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\cdot\sin^2\theta\cdot e^{\pm 2i\phi}$$

- Radialni del valovne funkcije:

$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2 R(r)}{\partial r^2} + \frac{2}{r}\frac{\partial R(r)}{\partial r}\right) + \frac{\hbar^2 l(l+1)}{2mr^2}R(r) + U(r)R(r) = ER(r)$$

Vir: internet

6.2 Kvantni rotator

- Rotacijska energija:

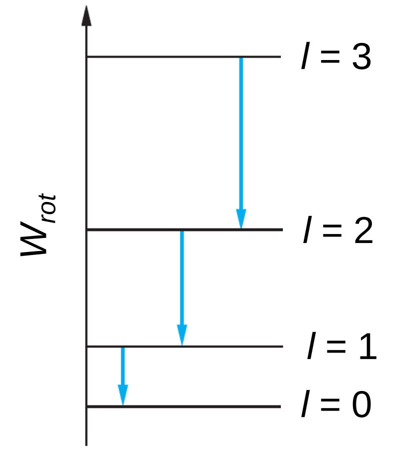
$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2 R(r)}{\partial r^2}+\frac{2}{r}\frac{\partial R(r)}{\partial r}\right)+\frac{\hbar^2 l(l+1)}{2mr^2}R(r)+U(r)R(r)=ER(r)$$

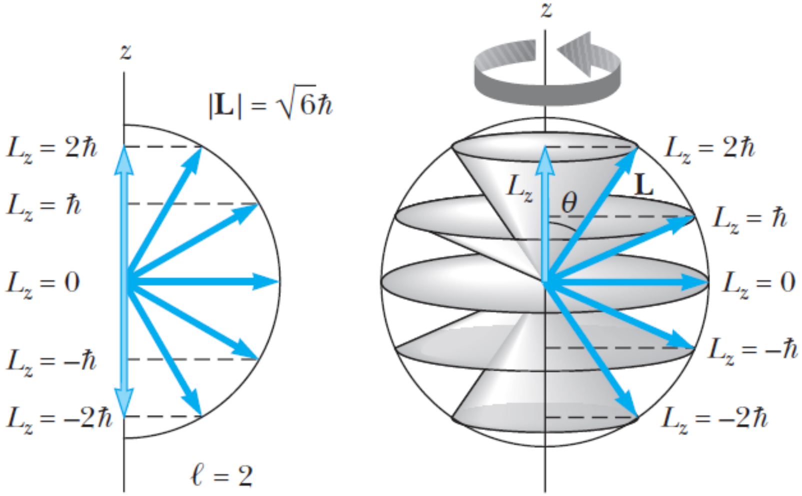
- Vrtilna količina: $\hat{L}^2\, Y_l^m(\theta,\phi)=l(l+1)\hbar^2\, Y_l^m(\theta,\phi)$

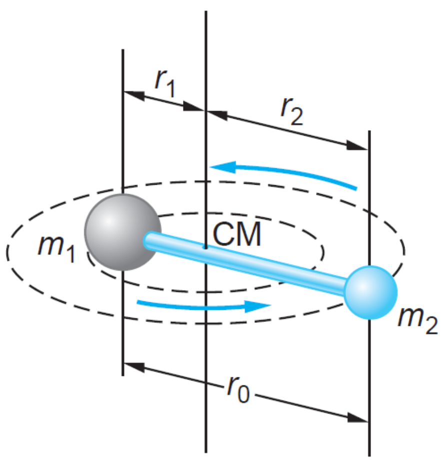
$$\hat{L}^z\, Y_l^m(\theta,\phi)=m\hbar\, Y_l^m(\theta,\phi)$$

$$\hat{W}_{rot}=\frac{\hat{L}^2}{2J}$$

$$\langle W_{rot}\rangle=\frac{\hbar^2 l(l+1)}{2J}$$







- Vrtenje po sferi: r = konst. $\Theta(\theta)\Phi(\varphi)=Y_l^m(\theta,\phi)=A_m P_l^m(\theta)\mathrm{e}^{im\varphi}$

$$\int_\Omega Y_l^{m*}(\theta,\phi)Y_{l'}^{m'}(\theta,\phi)\sin\theta\mathrm{d}\theta\mathrm{d}\varphi=\delta_{l,l'}\,\delta_{m,m'}$$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

6.3 Atom vodika in njemu podobni atomi

- Elektrostatski potencial: $$U(r) = -\frac{Ze_0^2}{4\pi\epsilon_0 r}$$
- Radialna valovna enačba: $$-\frac{\hbar^2}{2m}\left(\frac{\partial^2 R(r)}{\partial r^2} + \frac{2}{r}\frac{\partial R(r)}{\partial r}\right) + \frac{\hbar^2 l(l+1)}{2mr^2}R(r) + -\frac{Ze_0^2}{4\pi\epsilon_0 r}R(r) = ER(r)$$
- Valovne funkcije: $$\Psi(r,\theta,\varphi,t) = \psi_{n,l,m}(r,\theta,\varphi)\mathrm{e}^{-iEt/\hbar} = R_{n,l}(r)Y_l^m(\theta,\varphi)\mathrm{e}^{-iEt/\hbar}$$
- Lastne energije: $$E_n = -\frac{1}{2}\frac{e_0^2}{4\pi\epsilon_0 r_B}\frac{Z^2}{n^2} = -E_0\frac{Z^2}{n^2}$$

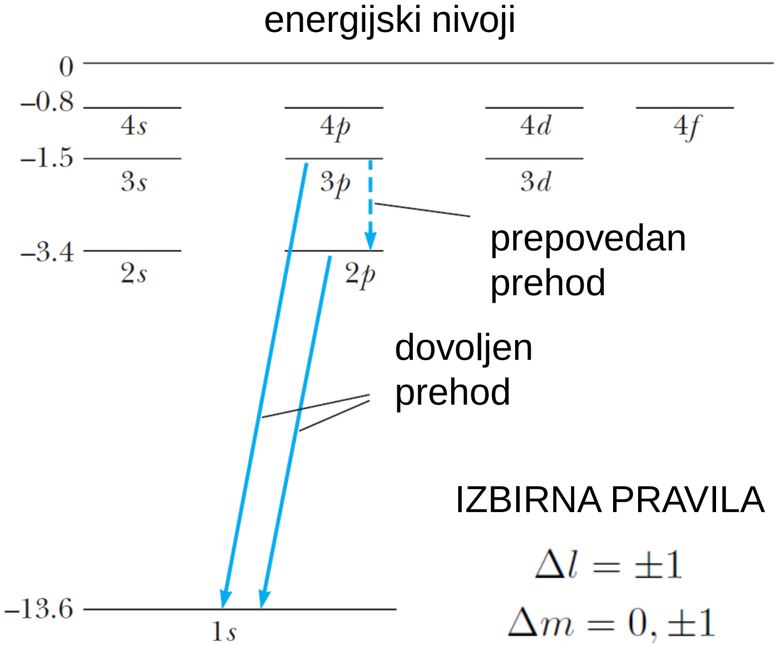
$$E_0 = \frac{1}{2}\frac{e_0^2}{4\pi\epsilon_0 r_B} = 13{,}6\ \mathrm{eV} \qquad r_B = \frac{4\pi\epsilon_0\hbar^2}{e_0^2 m_e} = \frac{\hbar^2 c^2}{\alpha m_e c^2}$$

- Kvantna števila:
  1. glavno kvantno število (energija)

     $$n \in \mathbb{N}$$
  2. orbitalno kvantno število (vrtilna količina)

     $$l = 0, 1, \ldots, n-1$$
  3. magnetno kvantno število (projekcija vrtilne količine)

     $$m = -l, -l+1, \ldots, l-1, l$$



IZBIRNA PRAVILA

$$\Delta l = \pm 1$$

$$\Delta m = 0, \pm 1$$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.3 Atom vodika in njemu podobni atomi

- Degeneracija:

$$d = n + 2 \times (n-1) + 2 \times (n-2) + \ldots + 2 \times 1 = n^2$$

- Radialne valovne funkcije: $R_{n,l}(r)$

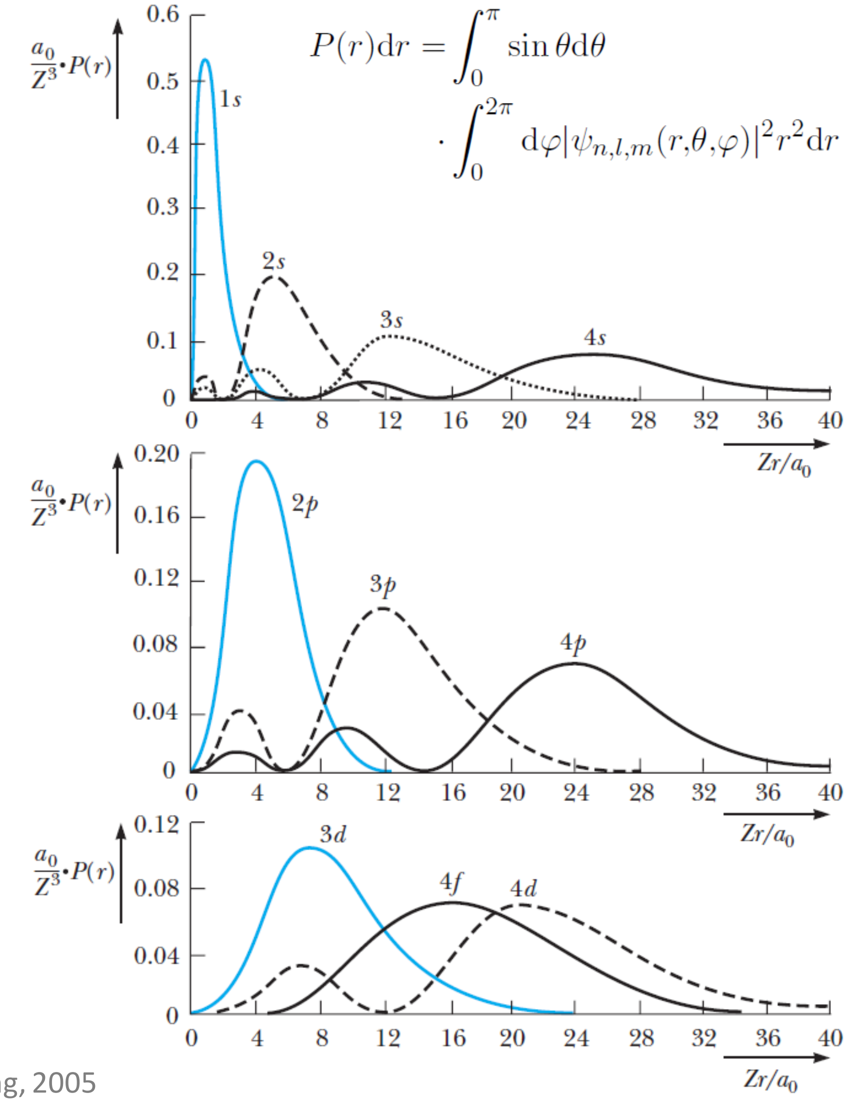
n	ℓ	$R_{n\ell}(r)$
1	0	$\left(\frac{Z}{a_0}\right)^{3/2} 2e^{-Zr/a_0}$
2	0	$\left(\frac{Z}{2a_0}\right)^{3/2}\left(2-\frac{Zr}{a_0}\right)e^{-Zr/2a_0}$
2	1	$\left(\frac{Z}{2a_0}\right)^{3/2}\frac{Zr}{\sqrt{3}\,a_0}e^{-Zr/2a_0}$
3	0	$\left(\frac{Z}{3a_0}\right)^{3/2} 2\left[1-\frac{2Zr}{3a_0}+\frac{2}{27}\left(\frac{Zr}{a_0}\right)^2\right]e^{-Zr/3a_0}$
3	1	$\left(\frac{Z}{3a_0}\right)^{3/2}\frac{4\sqrt{2}}{3}\frac{Zr}{a_0}\left(1-\frac{Zr}{6a_0}\right)e^{-Zr/3a_0}$
3	2	$\left(\frac{Z}{3a_0}\right)^{3/2}\frac{2\sqrt{2}}{27\sqrt{5}}\left(\frac{Zr}{a_0}\right)^2 e^{-Zr/3a_0}$

- Število vozlov:

$$n_v = n - l - 1$$

- Radialna verjetnostna gostota:

$$P(r)\mathrm{d}r = \int_0^{\pi} \sin\theta \mathrm{d}\theta \cdot \int_0^{2\pi} \mathrm{d}\varphi |\psi_{n,l,m}(r,\theta,\varphi)|^2 r^2 \mathrm{d}r$$



Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

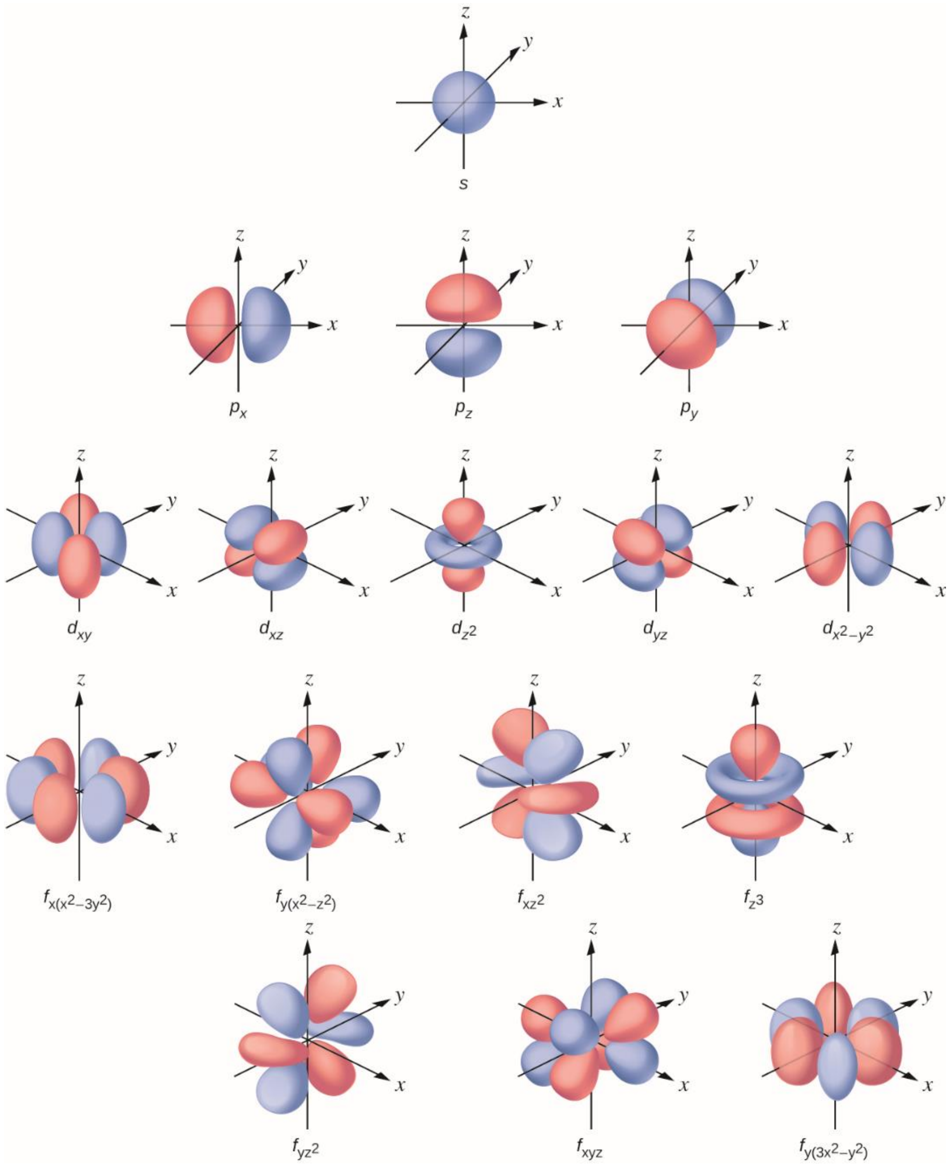
- Lastne valovne funkcije:

$l = 0$

$l = 1$

$l = 2$

$l = 3$



SIMULACIJA

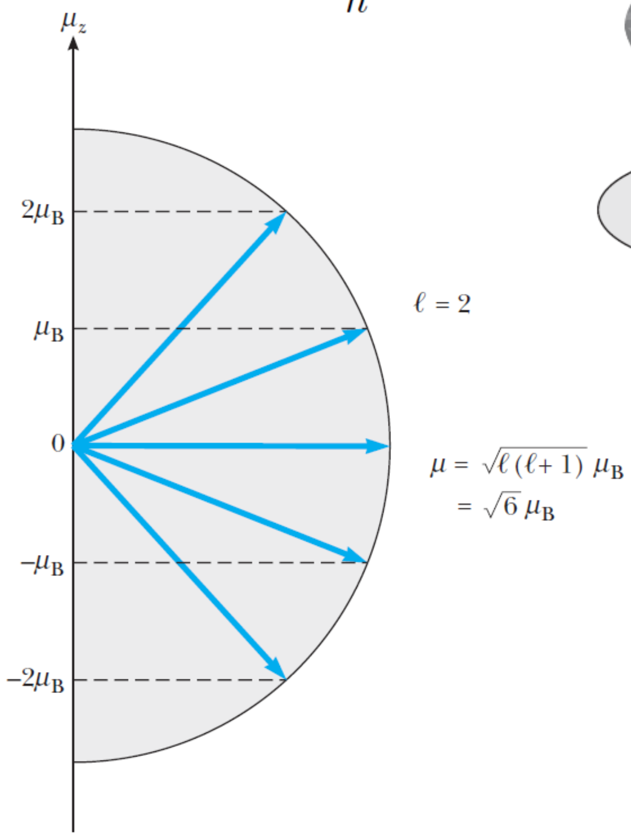
Vir: internet

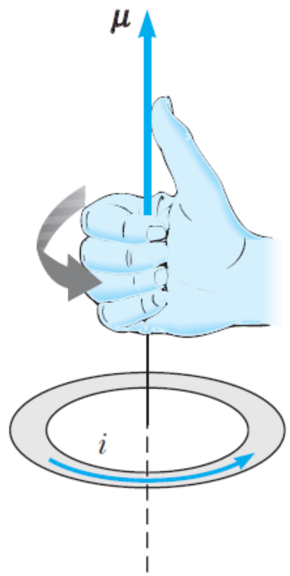
6.4 Atomski magnetizem

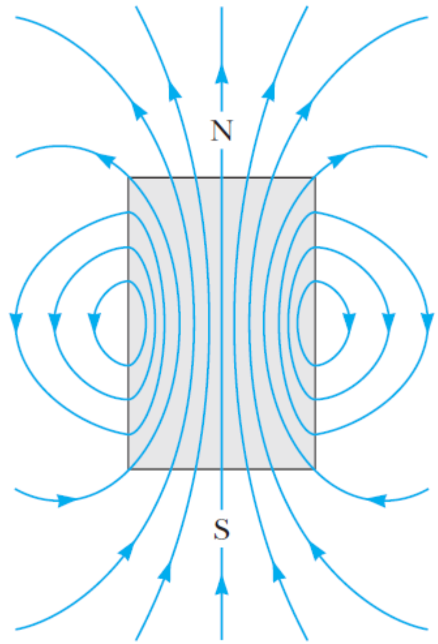
- Magnetni moment atoma:

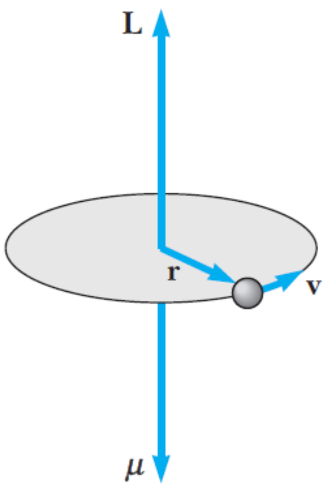
$$\vec{\mu} = -\frac{e_0}{2m_e}\vec{L} = -\frac{\mu_B}{\hbar}\vec{L}$$

$$\mu_z = -\frac{\mu_B}{\hbar}L_z$$









- Bohrov magneton:

$$\mu_B = \frac{e_0\hbar}{2m_e} = 9{,}27 \times 10^{-24}\ \mathrm{Am}^2$$

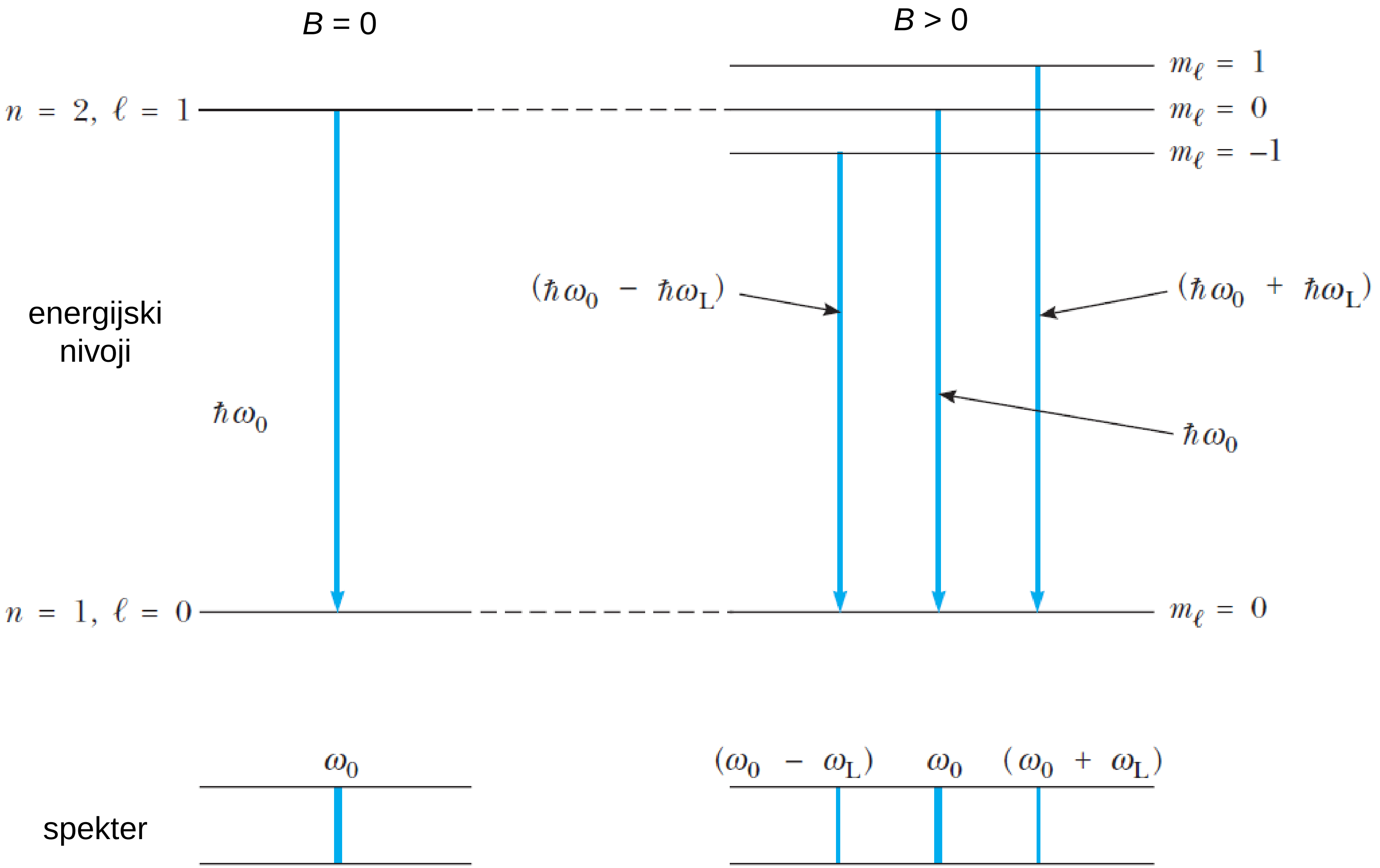
- Kvantizacija momenta:

$$\mu_z = -\mu_B m$$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.4 Atomski magnetizem

- Zunanje magnetno polje: $E_m = -\vec{\mu} \cdot \vec{B} = \mu_B B m = \hbar\omega_L m$



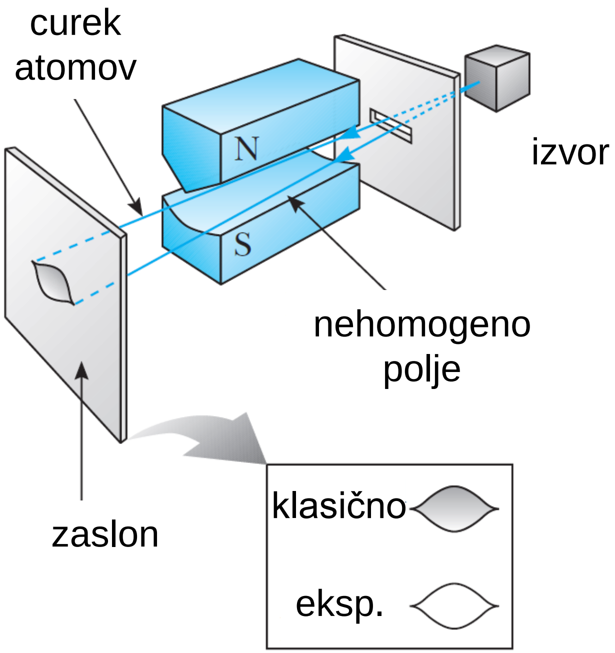
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.5 Spin elektrona

- Stern-Gerlachov poskus:

$$\mu = \pm\mu_B = 2\mu_B m_s$$

$$s = \frac{1}{2} \qquad m_s = \pm\frac{1}{2}$$



The Nobel Prize in Physics 1943

Otto Stern
Prize share: 1/1

The Nobel Prize in Physics 1943 was awarded to Otto Stern *"for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"*.

SIMULACIJA

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.5 Spin elektrona

- Spinska vrtilna količina:

$$|\vec{S}| = \sqrt{s(s+1)}\hbar = \frac{\sqrt{3}}{2}\hbar$$

$$|\vec{S_z}| = m_s\hbar = \pm\frac{1}{2}\hbar$$

- Spinski magnetni moment:

$$\vec{\mu_s} = -g\frac{\mu_B}{\hbar}\vec{S} \qquad g = 2{,}0023$$

- Skupni magnetni moment:

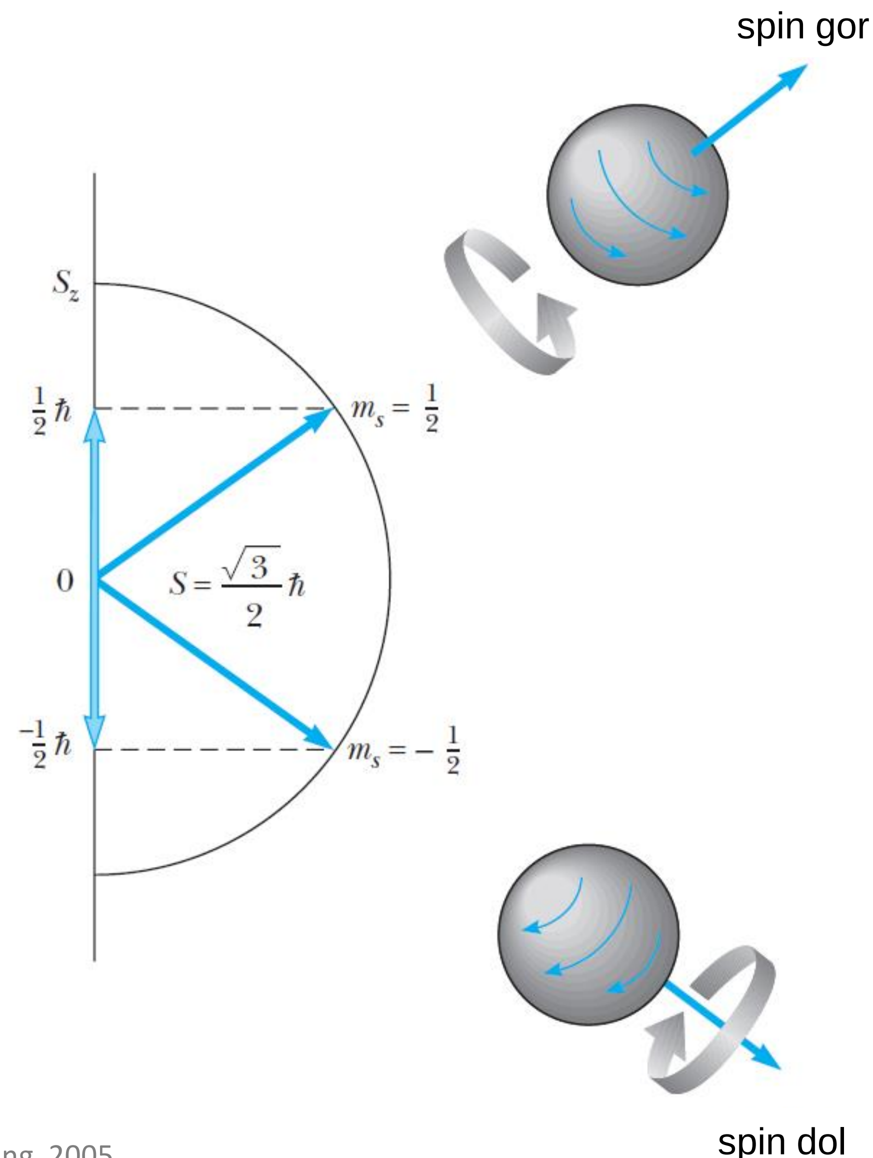
$$\vec{\mu} = \vec{\mu_o} + \vec{\mu_s} = -\frac{\mu_B}{\hbar}(\vec{L} + g\vec{S})$$

- Lastno stanje (4 kvantna števila):

$$\psi_{n,l,m,m_s}(r,\theta,\varphi) = \psi_{n,l,m}(r,\theta,\varphi)\psi_s$$

$$\hat{S}^2\,\psi_{n,l,m,m_s} = s(s+1)\hbar^2\,\psi_{n,l,m,m_s}$$

$$\hat{S}^z\,\psi_{n,l,m,m_s} = m_s\hbar\,\psi_{n,l,m,m_s}$$

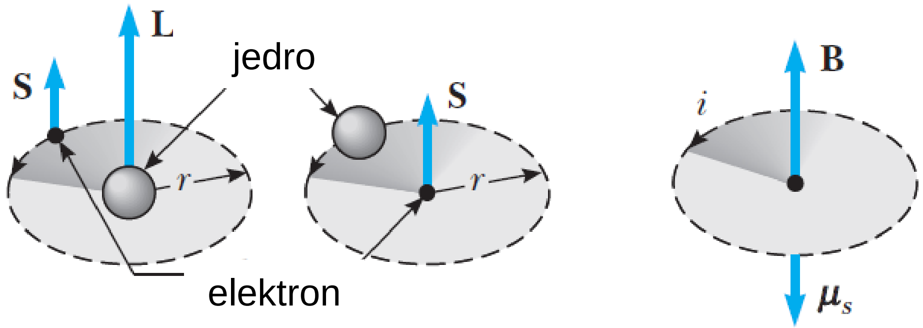


Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.6 Sklopitev spinske in tirne vrtilne količine

- Notranji Zeemanov efekt:

$$E_{LS} = \frac{e^2}{8\pi\epsilon_0 m^2 c^2}\left\langle\frac{1}{r^3}\right\rangle\langle\vec{L}\cdot\vec{S}\rangle = \frac{\lambda_{LS}}{\hbar^2}\langle\vec{L}\cdot\vec{S}\rangle$$

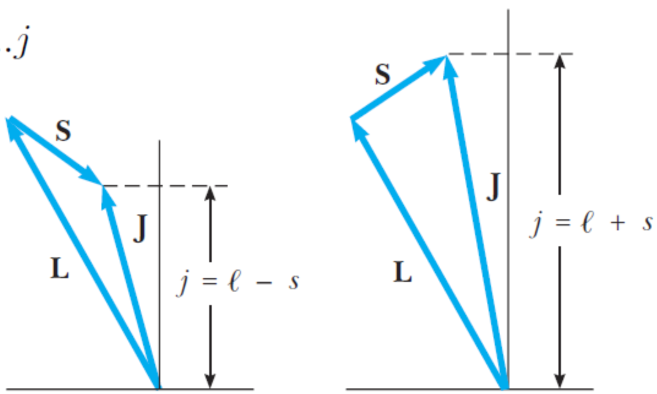


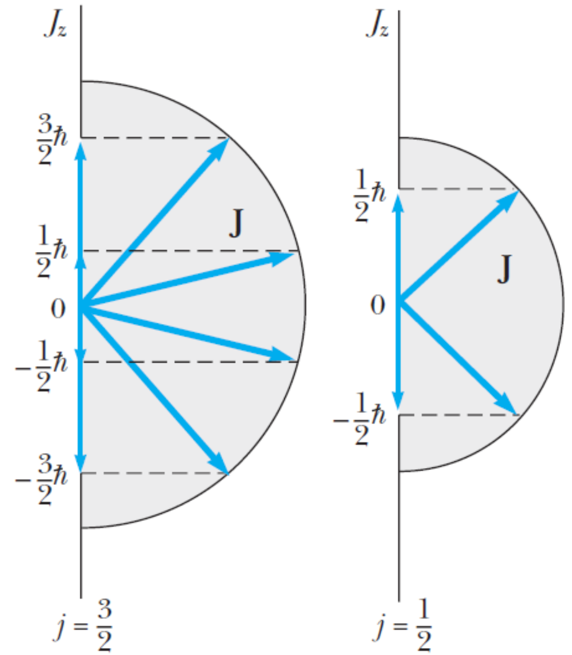
- Skupna vrtilna količina: $\vec{J} = \vec{L} + \vec{S}$

$$\hat{J}^2\,\psi_{n,l,j,m_j} = j(j+1)\hbar^2\,\psi_{n,l,j,m_j}$$
$$\hat{J}^z\,\psi_{n,l,j,m_j} = m_j\hbar\,\psi_{n,l,j,m_j}$$

- Novi kvantni števili:

$$|l-s| \leq j \leq l+s$$
$$m_j = -j, -j+1, \ldots j$$





Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.6 Sklopitev spinske in tirne vrtilne količine

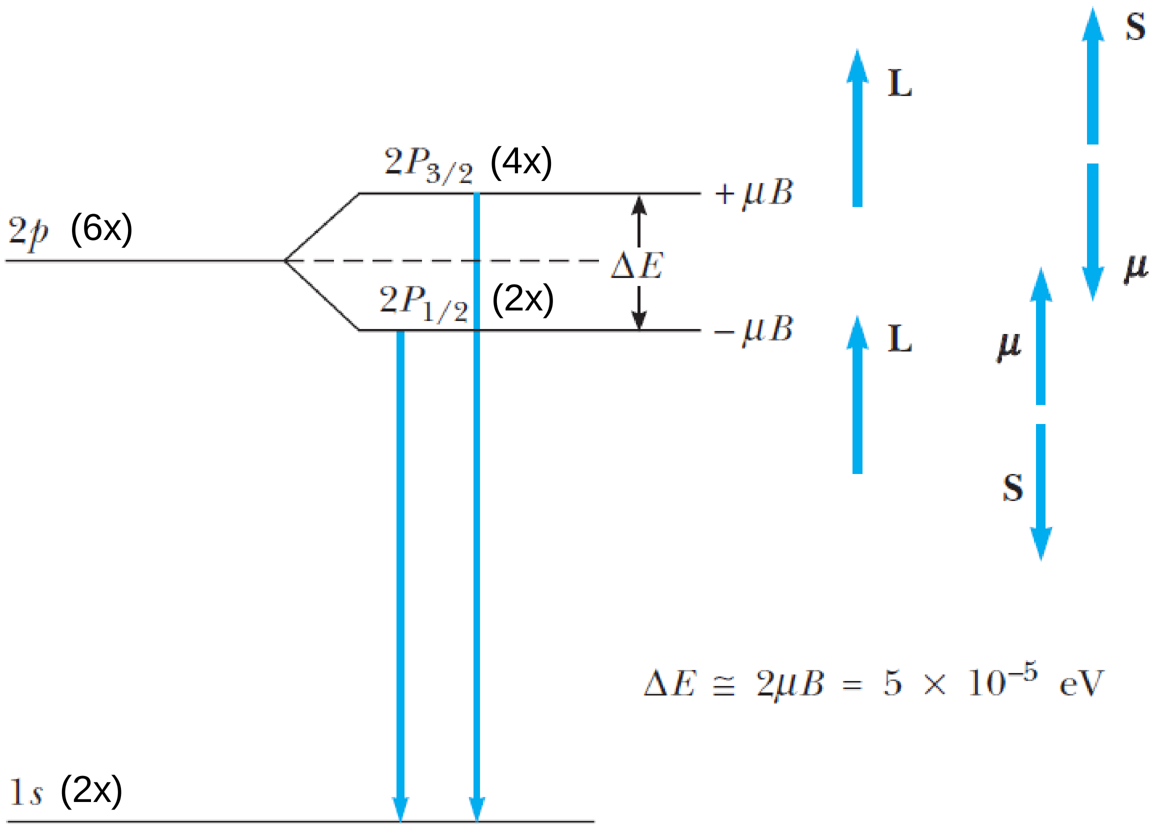
- Energijski razcep:

$$\langle \vec{L} \cdot \vec{S} \rangle = \frac{\langle J^2 \rangle - \langle L^2 \rangle - \langle S^2 \rangle}{2} = \frac{j(j+1) - l(l+1) - s(s+1)}{2}\hbar^2$$

2p:

$$\Delta E = \frac{3}{2}\lambda_{LS}$$

- Spektroskopske oznake: nL_j



$$\Delta E \cong 2\mu B = 5 \times 10^{-5}\ \text{eV}$$

- Notranje polje: $B_{int} \sim 1\ \text{T}$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.7 Zeemanov razcep

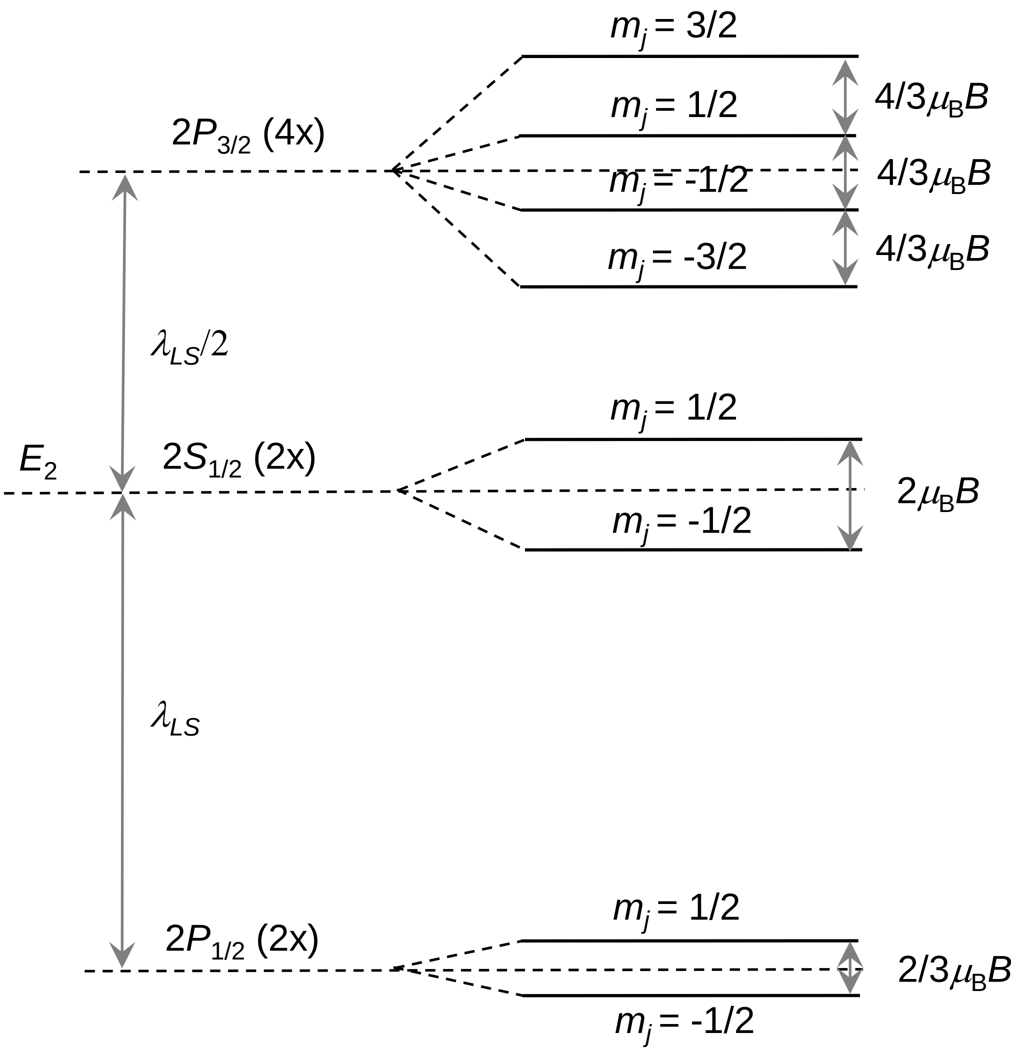
- Moment $\vec{\mu} = \vec{\mu_o} + \vec{\mu_s} = -\frac{\mu_B}{\hbar}(\vec{L} + g\vec{S})$ v zunanjem polju $\vec{B} \parallel \vec{c}$:

$$\hat{H}_z = \frac{\mu_B}{\hbar}(\hat{L}_z + g\hat{S}_z)B$$

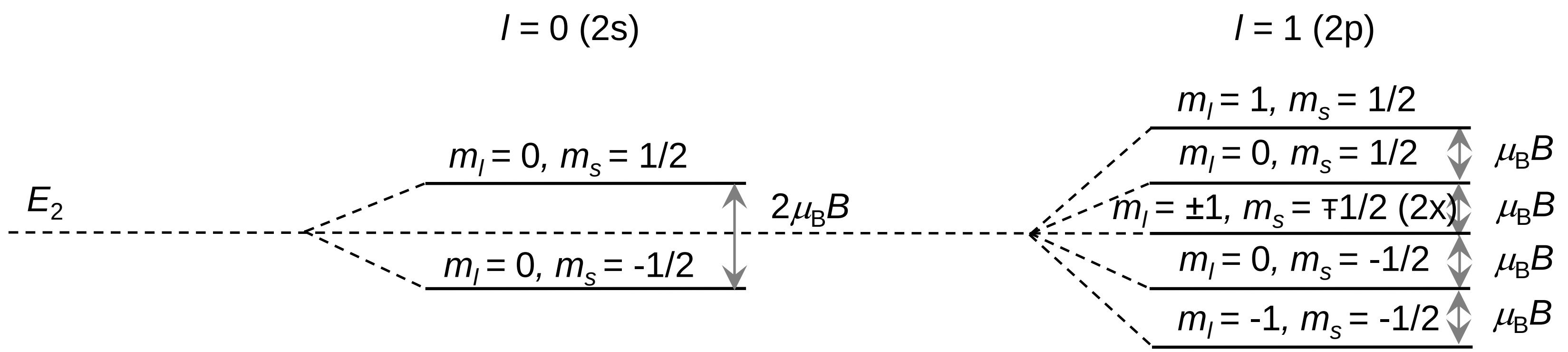
1. Šibko polje: $B \ll B_{int} \sim 1\ \mathrm{T}$

$$E_z = g_{lsj}\mu_B B m_j$$

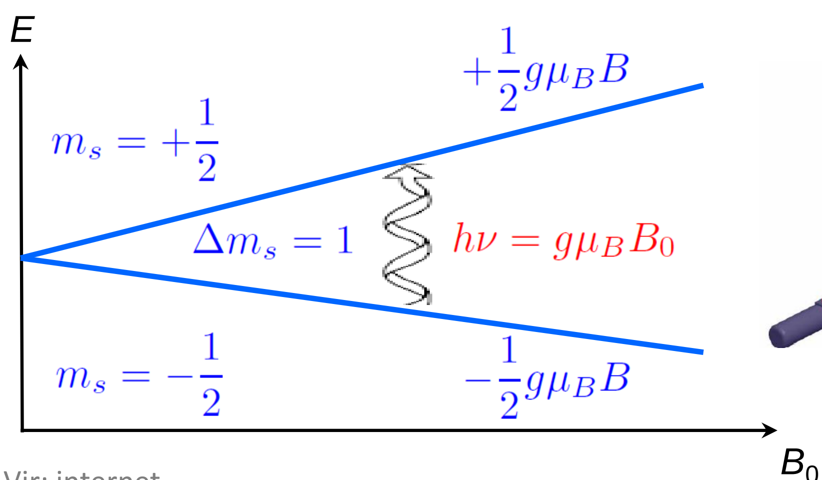
$$g_{lsj} = \frac{3}{2} - \frac{l(l+1) - s(s+1)}{2j(j+1)}$$

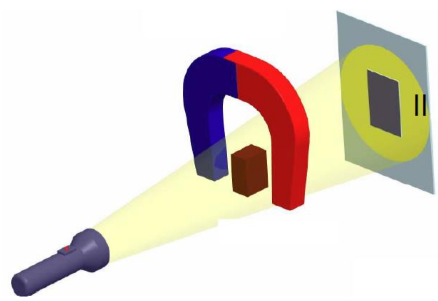


2. Močno polje: $B \gg B_{int} \sim 1\ \mathrm{T}$ → $E_z = \mu_B B(m + g m_s)$



- Elektronska spinska resonanca:





ESR spektrometer (IJS)

Vir: internet

- Paulijevo izključitveno načelo: atomsko stanje (n, l, j, m_j) oz. (n, l, m, m_s) največ enkrat zasedeno!
- Neločljivost identičnih delcev v kvantni mehaniki (izmenjalna simetrija):

$$|\psi(\vec{r}_1, \vec{r}_2)|^2 = |\psi(\vec{r}_2, \vec{r}_1)|^2$$

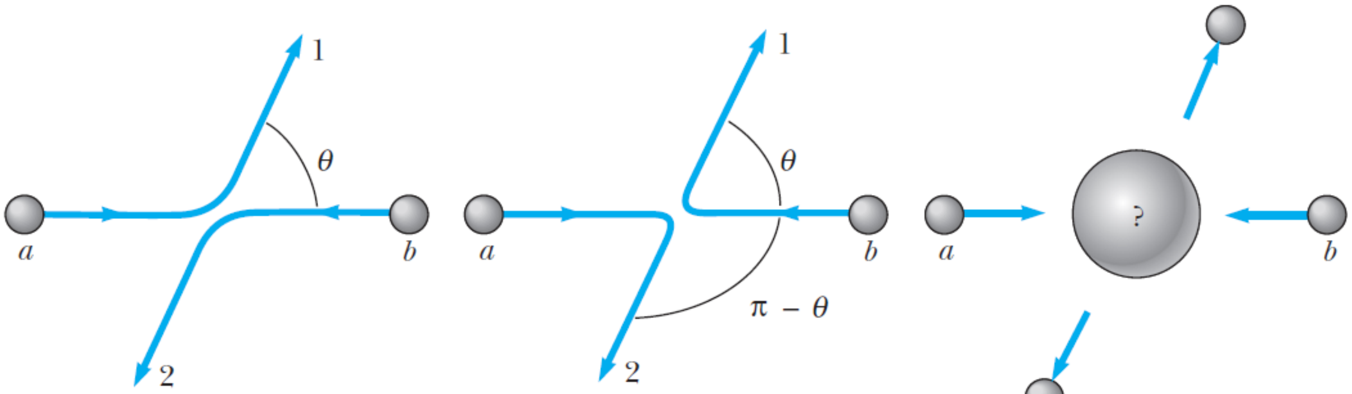
BOZONI: $\psi(\vec{r}_1, \vec{r}_2) = \psi(\vec{r}_2, \vec{r}_1)$

FERMIONI: $\psi(\vec{r}_1, \vec{r}_2) = -\psi(\vec{r}_2, \vec{r}_1)$

The Nobel Prize in Physics 1945

Wolfgang Pauli
Prize share: 1/1

The Nobel Prize in Physics 1945 was awarded to Wolfgang Pauli *"for the discovery of the Exclusion Principle, also called the Pauli*



klasičen pogled KM pogled

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.8 Atomi z več elektroni

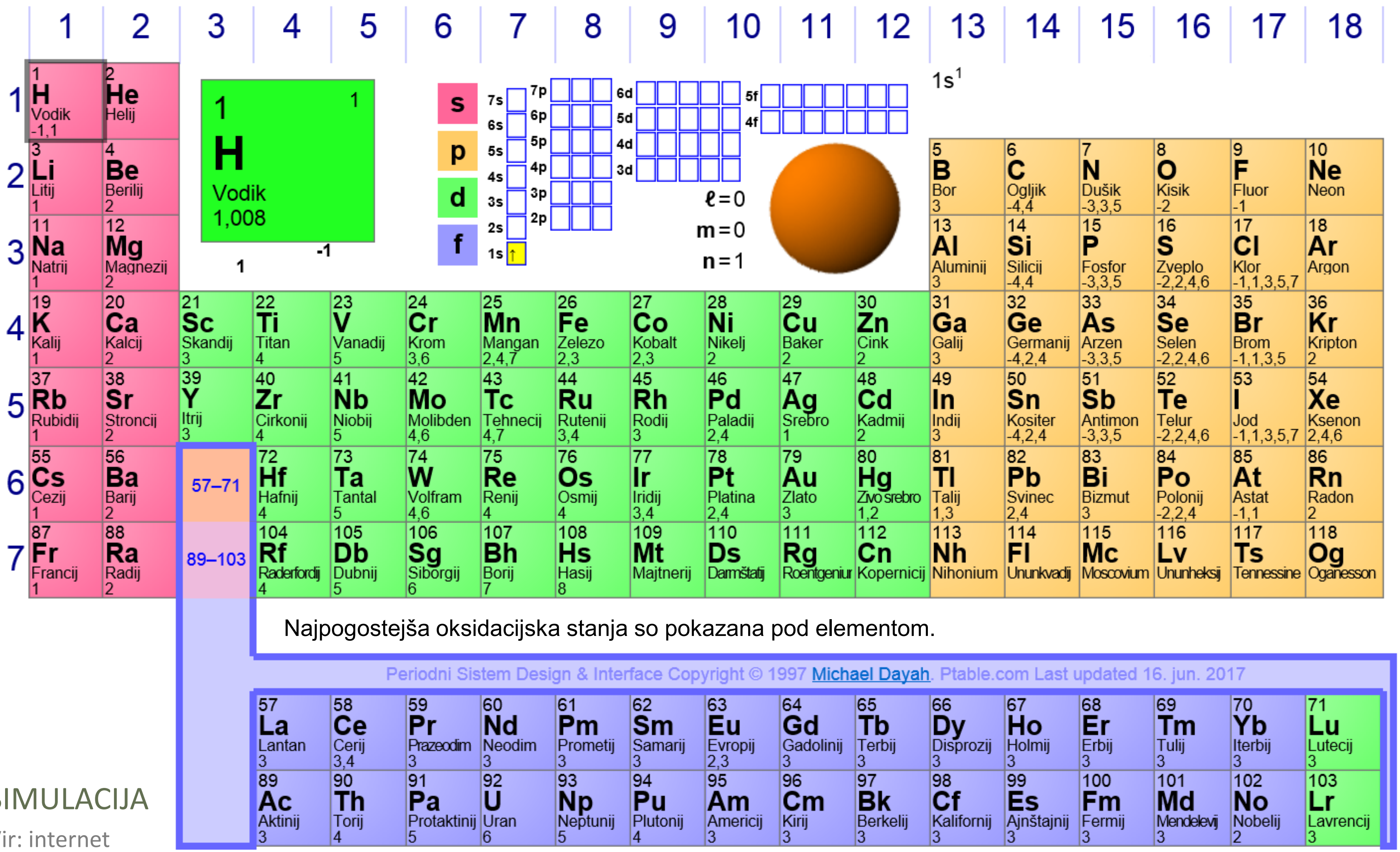
- Elektronska konfiguracija:

Atom	1s	2s	2p			Konfiguracija
Li	↑↓	↑				$1s^2 2s^1$
Be	↑↓	↑↓				$1s^2 2s^2$
B	↑↓	↑↓	↑			$1s^2 2s^2 2p^1$
C	↑↓	↑↓	↑	↑		$1s^2 2s^2 2p^2$
N	↑↓	↑↓	↑	↑	↑	$1s^2 2s^2 2p^3$
O	↑↓	↑↓	↑↓	↑	↑	$1s^2 2s^2 2p^4$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

6.8 Atomi z več elektroni

➢ Periodni sistem elementov:



SIMULACIJA

Vir: internet

Univerza v Ljubljani
Fakulteta za matematiko in fiziko

MODERNA FIZIKA

Kvantna mehanika 5
Molekule

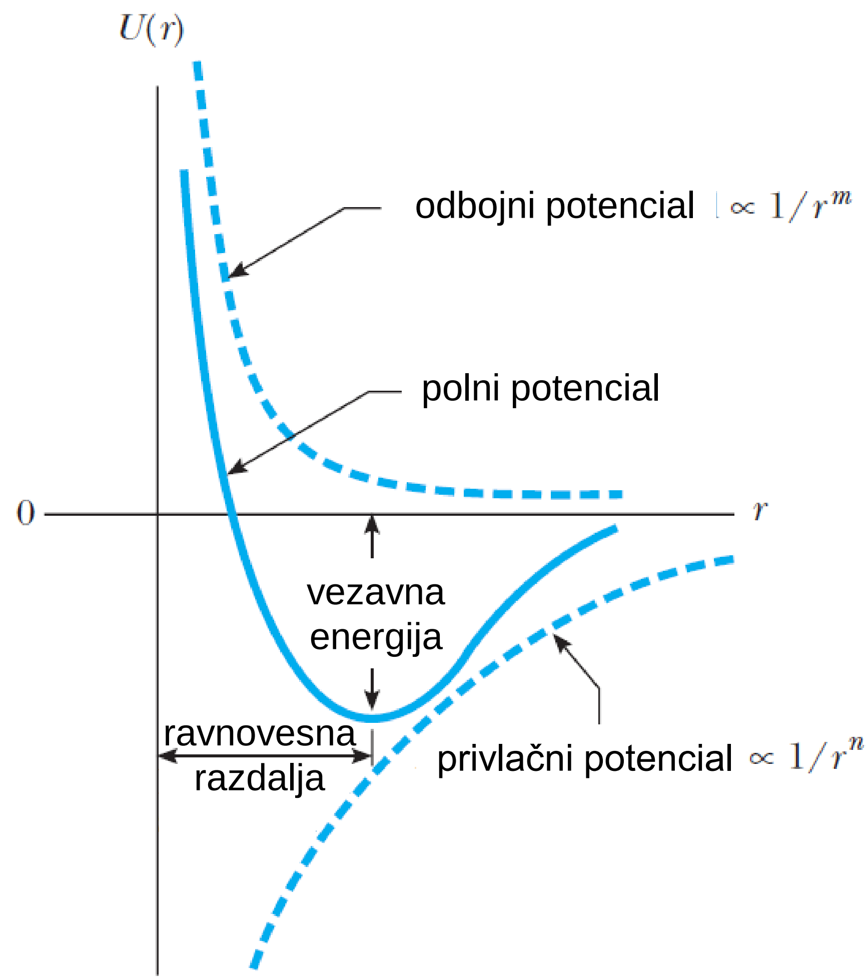
Andrej Zorko
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

7.1 Povezovanje atomov v molekule in tipi vezi

- Molekulske vezi: izključitveno načelo in tuneliranje

- Molekulski potencial:

$$U(r) = -\frac{A}{r^n} + \frac{B}{r^m}$$



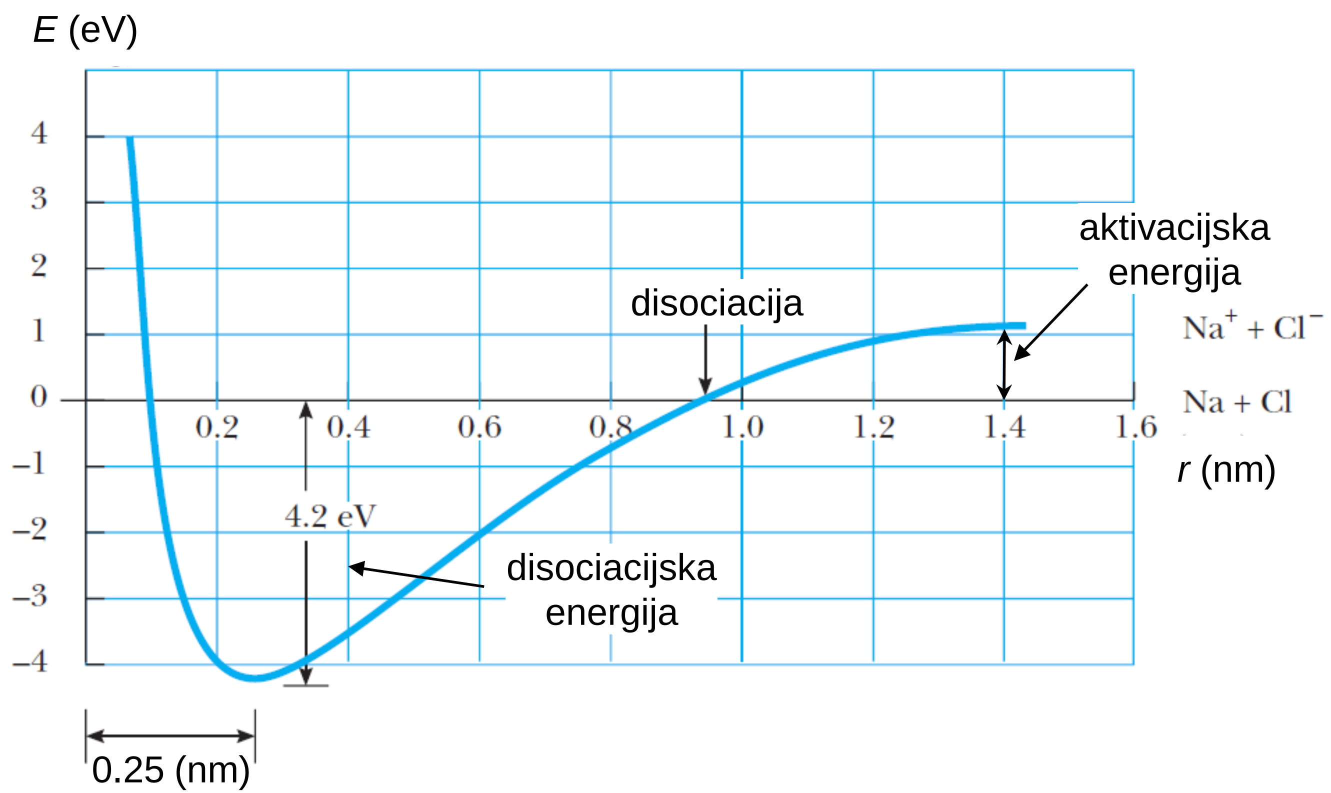
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

7.1 Povezovanje atomov v molekule in tipi vezi

- Tipi molekulskih vezi

  1. Ionska vez:

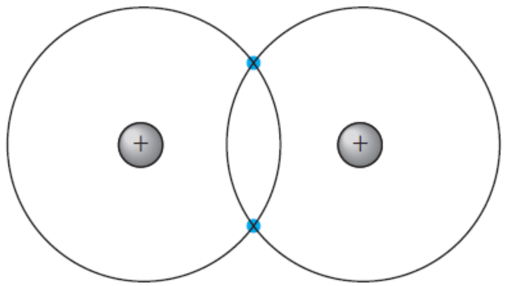
- ionizacijska energija
- elektronska afiniteta
- aktivacijska energija
- disociacijska energija

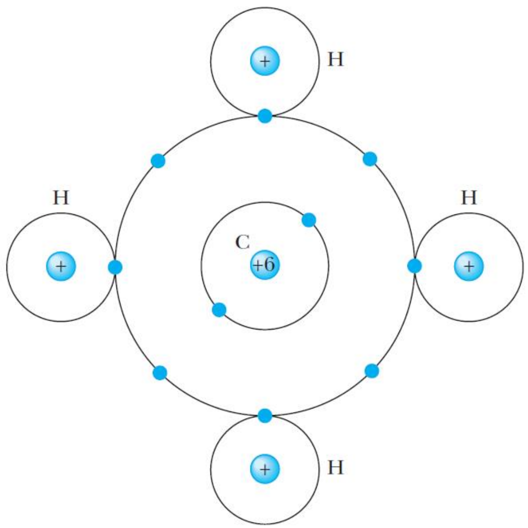


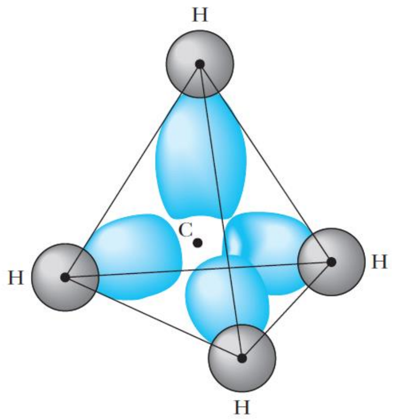
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

7.1 Povezovanje atomov v molekule in tipi vezi

2. Kovalentna vez: molekulske orbitale

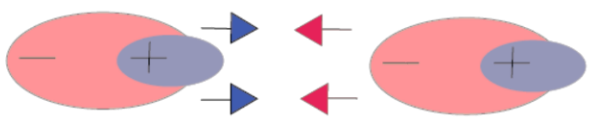






3. Van der Wallsova vez:

privlak



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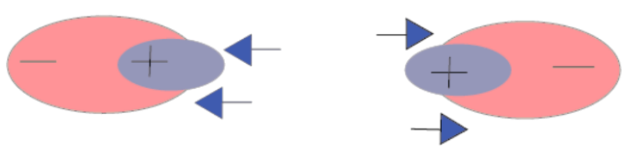
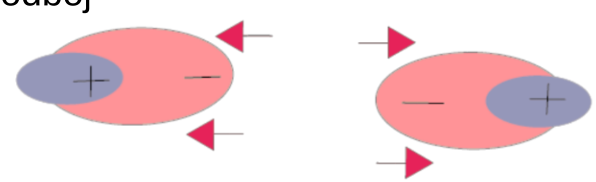
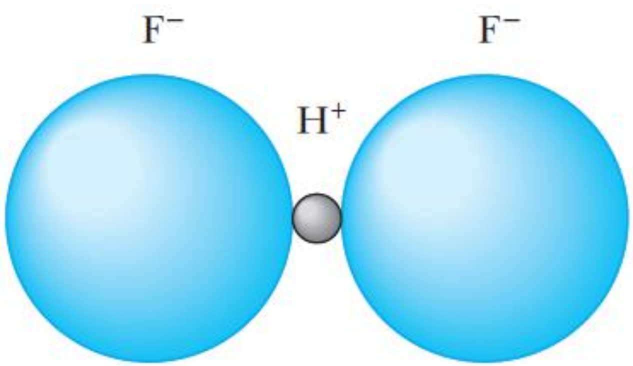


odboj



4. Vodikova vez:



Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

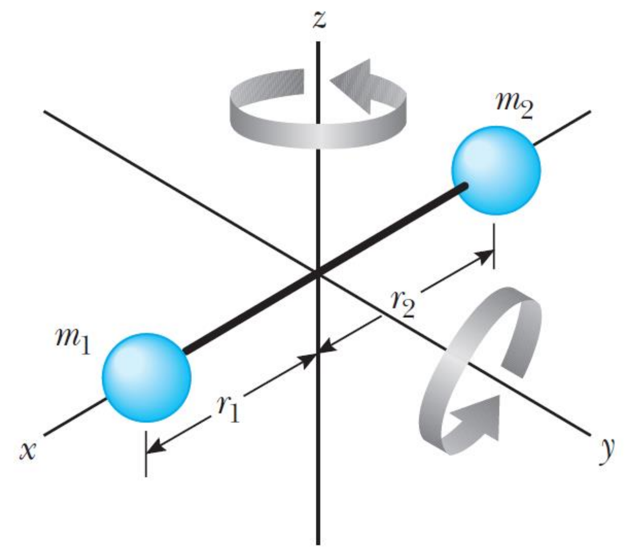
7.2 Rotacijska in vibracijska vzbujena stanja molekul

- Rotacije molekul:

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

$$J = m_r r^2$$

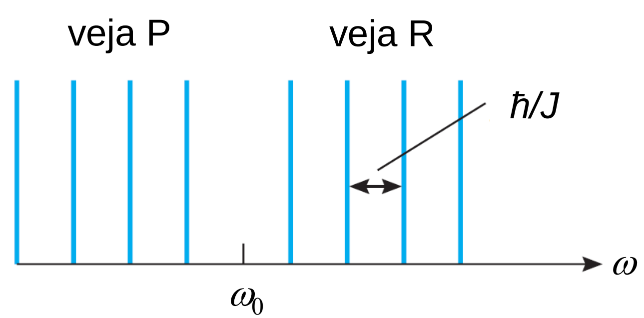
$$\frac{1}{m_r} = \frac{1}{m_1} + \frac{1}{m_2} \qquad r = r_1 + r_2$$

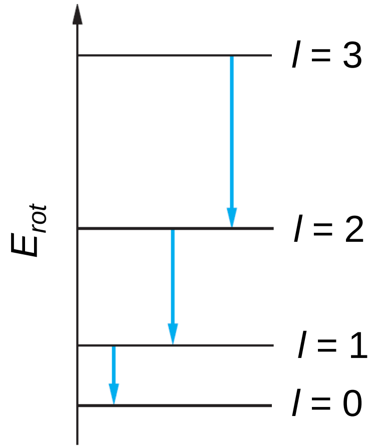


- Absorpcijski spekter: $\Delta l = \pm 1$

1. veja P: $l \to l-1$ $\qquad \Delta E_P^l = -\frac{\hbar^2}{J} l$

2. veja R: $l \to l+1$ $\qquad \Delta E_R^l = \frac{\hbar^2}{J}(l+1)$



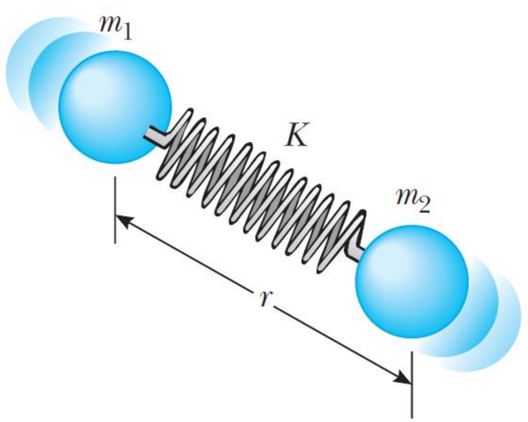


Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

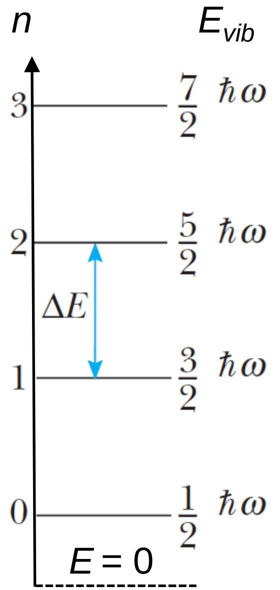
- Vibracije molekul:

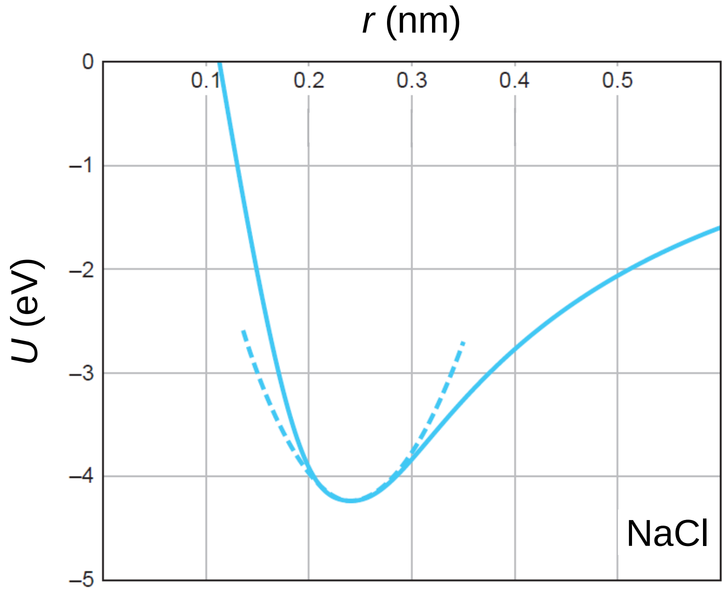
$$E_{vib}^{n} = \left(n + \frac{1}{2}\right)\hbar\omega$$

$$\omega = \sqrt{\frac{K}{m_r}} \qquad K = \left.\frac{\mathrm{d}^2U(r)}{\mathrm{d}r^2}\right|_{r=r_0}$$



- Absorpcijski spekter: $\Delta n = \pm 1 \qquad \Delta E_{vib} = \hbar\omega$





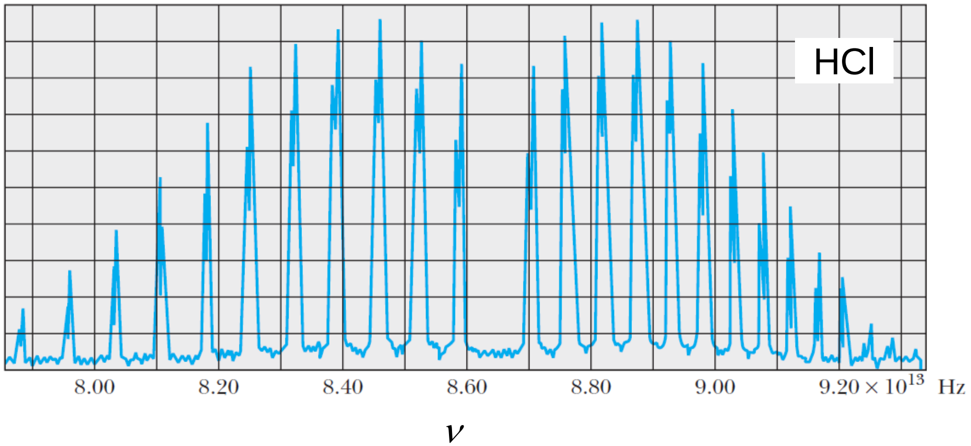
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

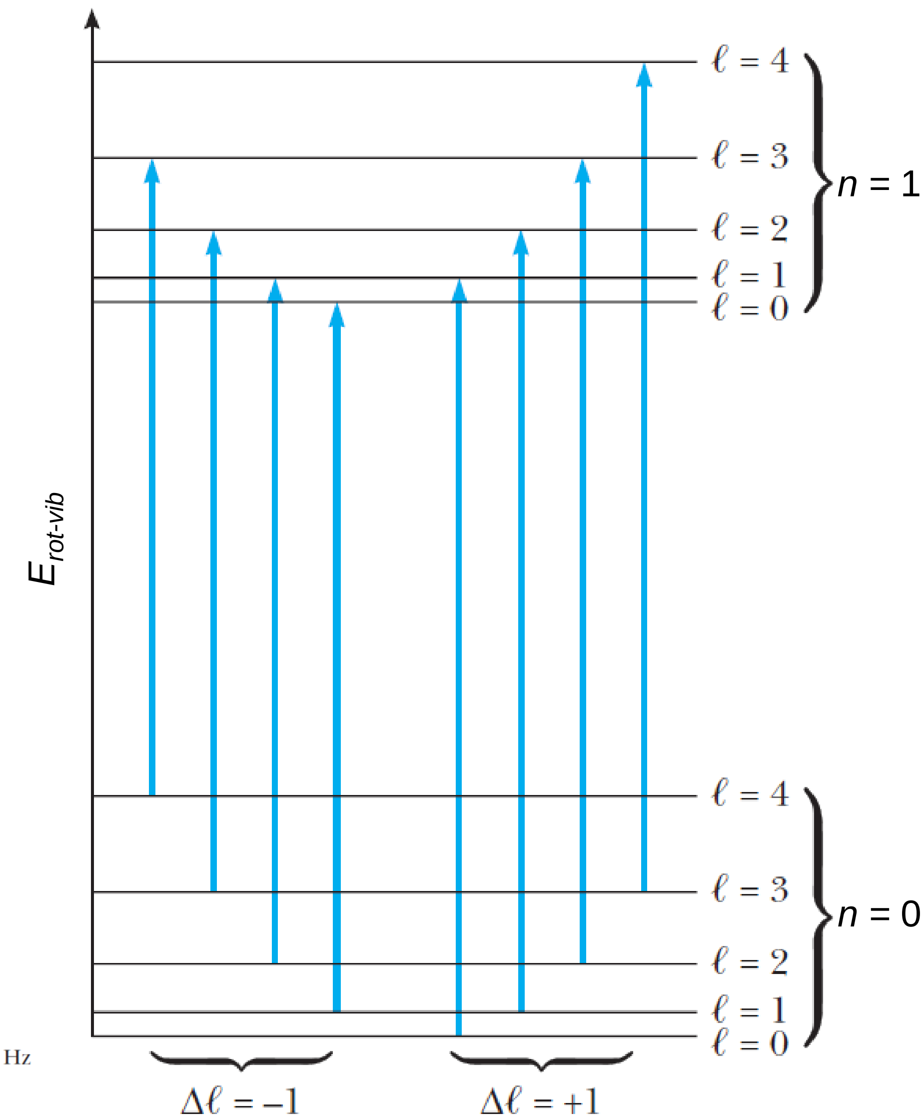
- Rotacijsko-vibracijski spekter:

$$E_{rot-vib}^{l,n} = \frac{\hbar^2}{2J} l(l+1) + \left(n + \frac{1}{2}\right)\hbar\omega$$

- Izbirna pravila za optične prehode:

$$\Delta l = \pm 1$$
$$\Delta n = \pm 1$$



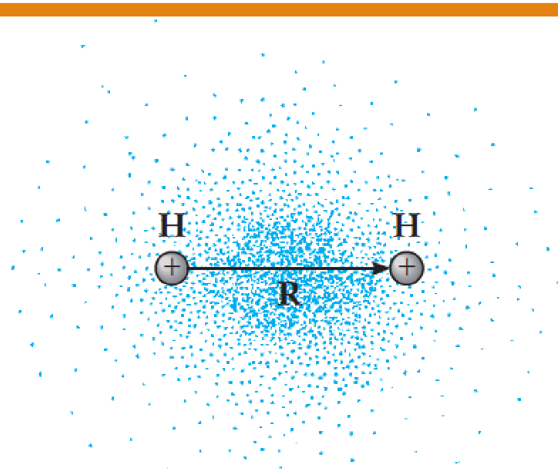


Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

1. Molekula H_2^+:

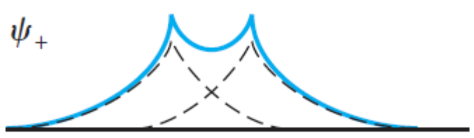
$$U(\vec{r}) = -\frac{e^2}{4\pi\epsilon_0|\vec{r}|} - \frac{e^2}{4\pi\epsilon_0|\vec{r}-\vec{R}|}$$

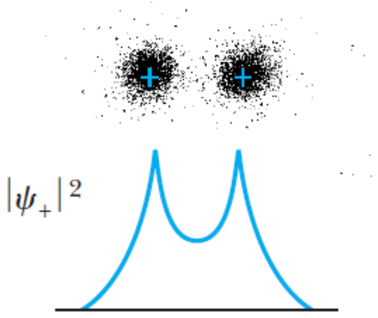
$$U_j(\vec{r}) = \frac{e^2}{4\pi\epsilon_0|\vec{R}|}$$



- Simetrična funkcija:

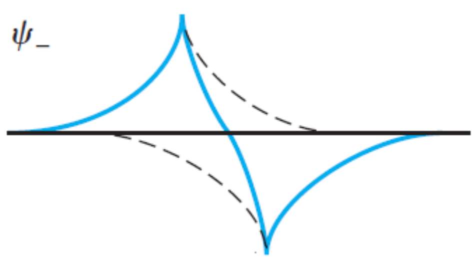
$$\psi_+(\vec{r}) = \psi_a(\vec{r}) + \psi_a(\vec{r}-\vec{R})$$

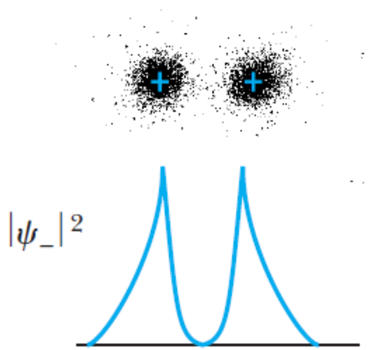




- Antisimetrična funkcija:

$$\psi_-(\vec{r}) = \psi_a(\vec{r}) - \psi_a(\vec{r}-\vec{R})$$





Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

7.3 Kvantnomehanski opis molekul

- Energija:

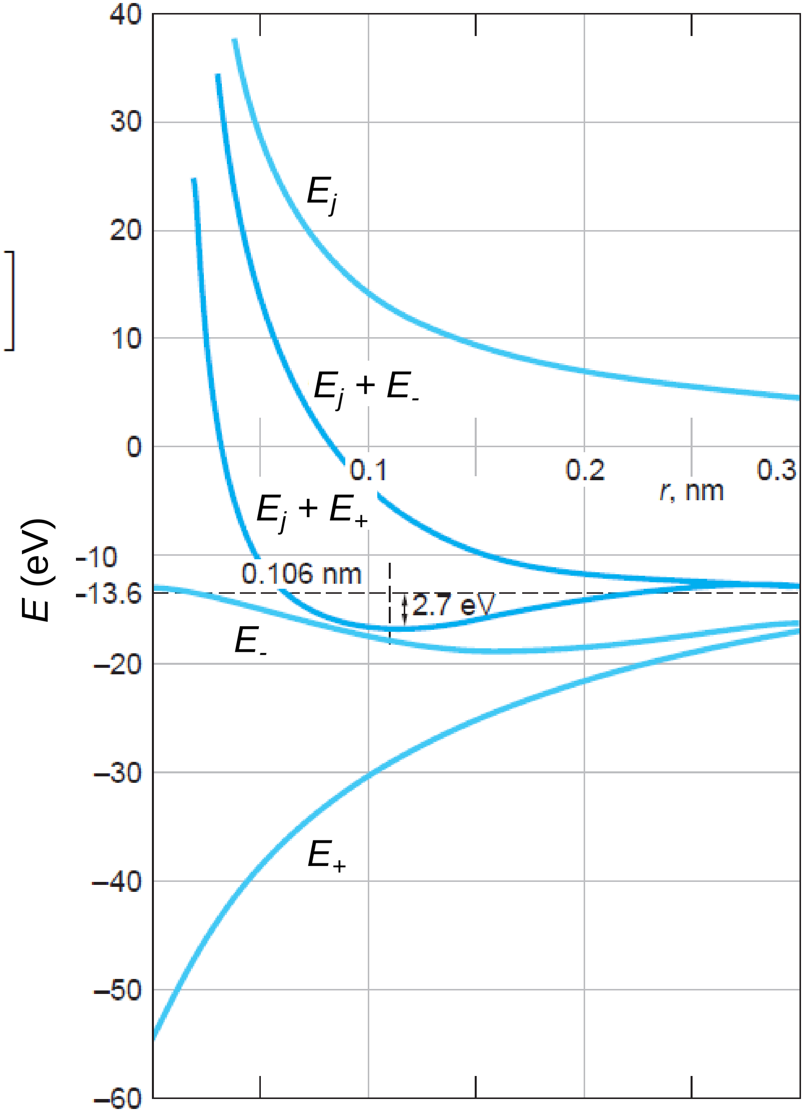
$$E_{\pm}(R) = -E_0\left[1 + \frac{2}{1 \pm (1 + R/r_B + R^2/3r_B)\mathrm{e}^{-R/r_B}} \times \right.$$
$$\left. \times \left(\frac{r_B}{R} - \frac{r_B}{R}\left(1 + \frac{R}{r_B}\right)\mathrm{e}^{-2R/r_B} \pm \left(1 + \frac{R}{r_B}\right)\mathrm{e}^{-R/r_B}\right)\right]$$

$$E_j = E_0 \frac{2r_B}{R}$$

$$E_v = -2{,}7\,\mathrm{eV}$$
$$R_0 = 0{,}106\,\mathrm{nm}$$

2. Molekula H_2:

$$E_v = -4{,}5\,\mathrm{eV}$$
$$R_0 = 0{,}074\,\mathrm{nm}$$



SIMULACIJA

Vir: internet; povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

Univerza *v Ljubljani*
Fakulteta za *matematiko in fiziko*

MODERNA FIZIKA

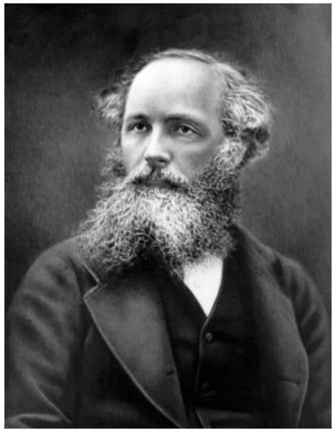
Statistična fizika

Andrej Zorko
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

8.1 Maxwell-Boltzmannova porazdelitev

- Osnovne predpostavke:

1. razločljivi identični delci
2. ravnovesna porazdelitev
3. majhna gostota/visoka temperatura



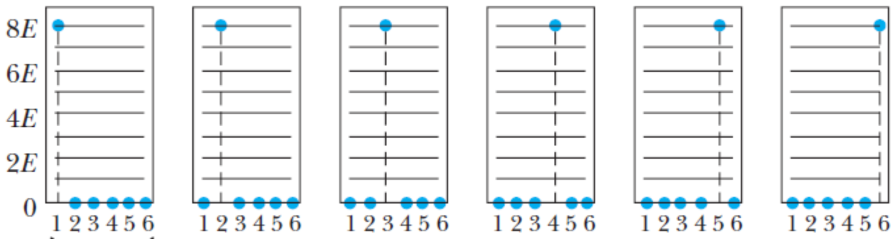
J. C. Maxwell

L. Boltzmann

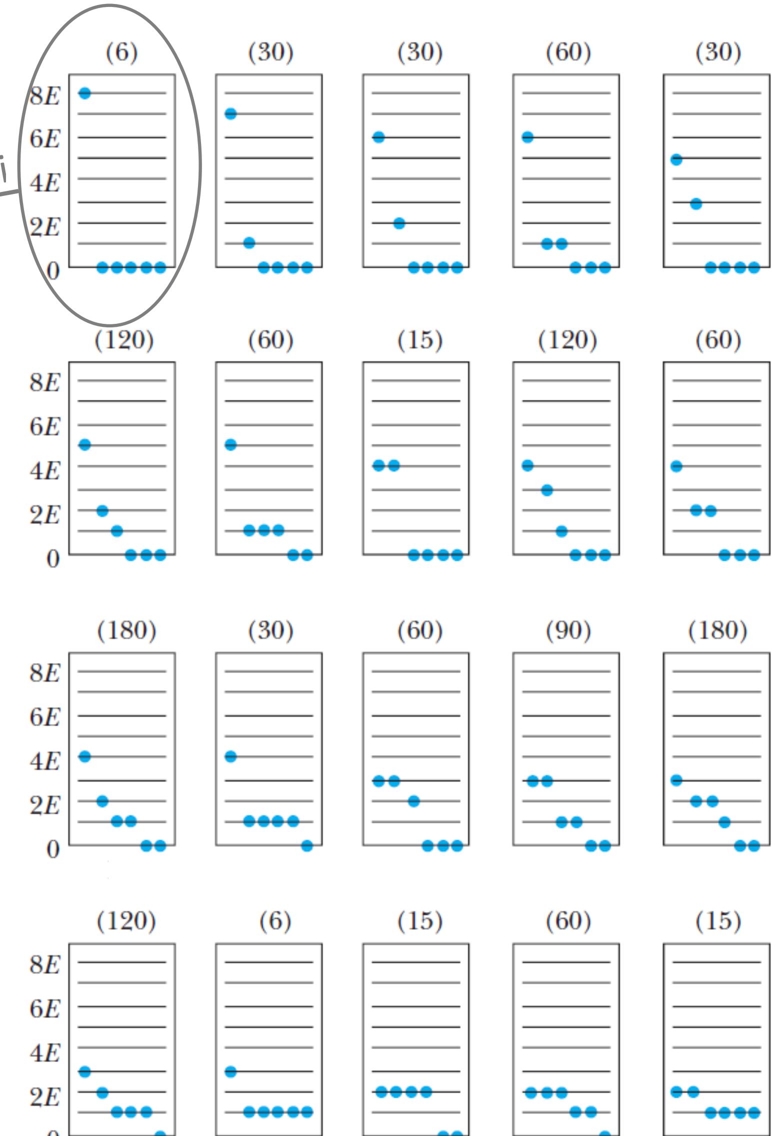
Vir: internet

8.1 Maxwell-Boltzmannova porazdelitev

- *Primer*: 6 delcev s skupno energijo 8*E*



razločljivi delci



- Št. mikrostanj za konfiguracijo:

$$N_{MB} = \frac{N!}{N_1!N_2!\ldots}$$

- Št. vseh mikrostanj:

$$N_0 = 1287$$

- Verjetnost za konfiguracijo:

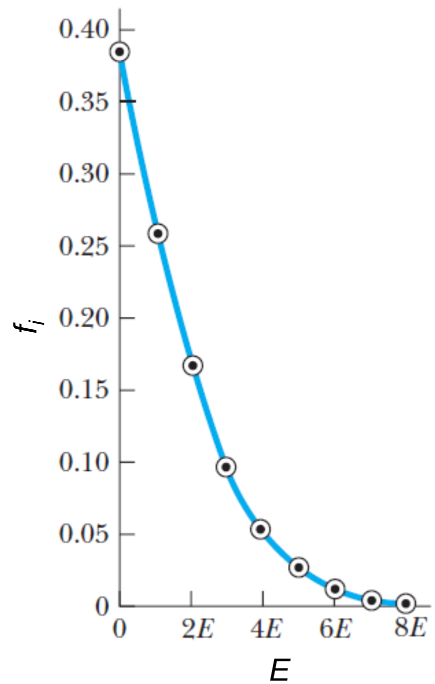
$$p_{MB} = \frac{N_{MB}}{N_0}$$

- Povprečna zasedenost:

$$\bar{N}_i = \sum_j N_i^j p_{MB}^j$$

- Verjetnost za energijo E_i:

$$f_i = \frac{\bar{N}_i}{6}$$



Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

8.1 Maxwell-Boltzmannova porazdelitev

- Osnovne predpostavke:

  1. fiksno število identičnih delcev
  2. fiksna skupna energija

DISKRETNA PORAZDELITEV

ZVEZNA PORAZDELITEV

- Porazdelitvena funkcija:

$$f^i_{MB} = A\mathrm{e}^{-E_i/k_BT}$$

$$f_{MB}(E) = A\mathrm{e}^{-E/k_BT}$$

- Degeneracija/gostota stanj (razpoložljiva stanja):

$$g^i$$

$$g(E)$$

- Število zasedenih stanj:

$$N^i = g_i f^i_{MB}$$

$$n(E)\mathrm{d}E = g(E) f_{MB}(E)\mathrm{d}E$$

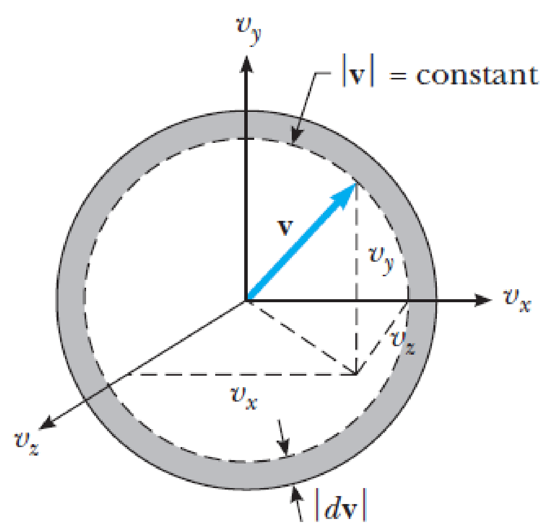
- Normalizacija:

$$N = \sum_i N^i = \sum_i g^i f^i_{MB}$$

$$\frac{N}{V} = \int_0^\infty n(E)\mathrm{d}E = \int_0^\infty g(E) f_{MB}(E)\mathrm{d}E$$

8.1 Maxwell-Boltzmannova porazdelitev

- Porazdelitev hitrosti molekul plina (točkasti neinteragirajoči delci): Maxwell l. 1859



- Gostota stanj v prostoru hitrosti:

$$g(v)\mathrm{d}v = C4\pi v^2\mathrm{d}v$$

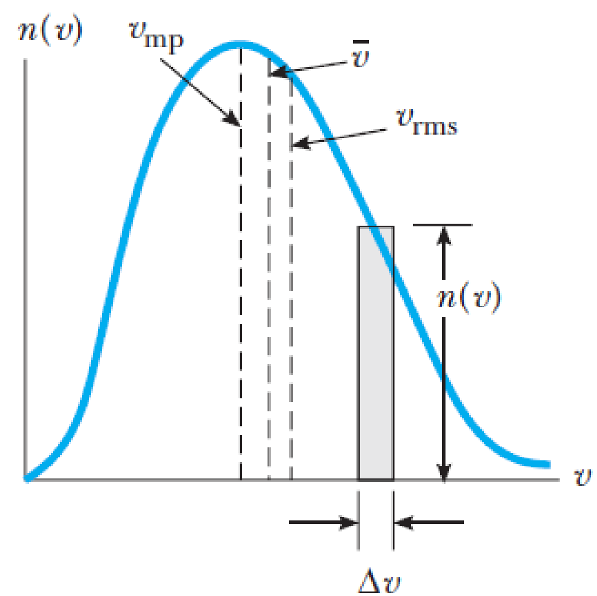
- Porazdelitev hitrosti:

$$n(E)\mathrm{d}E = n(v)\mathrm{d}v$$
$$= 4\pi\frac{N}{V}\left(\frac{m}{2\pi k_B T}\right)^{3/2} v^2 \mathrm{e}^{-mv^2/(2k_B T)}\mathrm{d}v$$

- Povprečja hitrosti:

$$\bar{v} = \sqrt{\frac{8k_B T}{\pi m}} \qquad \sqrt{\bar{v^2}} = \sqrt{\frac{3k_B T}{m}}$$

EKVIPARTICIJSKI IZREK



- Pogoj veljavnosti MB statistike:

$$\left(\frac{N}{V}\right)\frac{\hbar^3}{8\left(mk_B T\right)^{3/2}} \ll 1$$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

8.2 Kvantna statistika

- Kvantna narava delcev spremeni njihovo statistiko pri:

  1. velikih gostotah delcev
  2. majhnih masah delcev
  3. nizkih temperaturah

$$\left(\frac{N}{V}\right) \frac{\hbar^3}{8\,(mk_BT)^{3/2}} > 1$$

- Klasični (razločljivi) delci: $\psi_{MB} = \psi_a(\vec{r}_1)\psi_b(\vec{r}_2)$

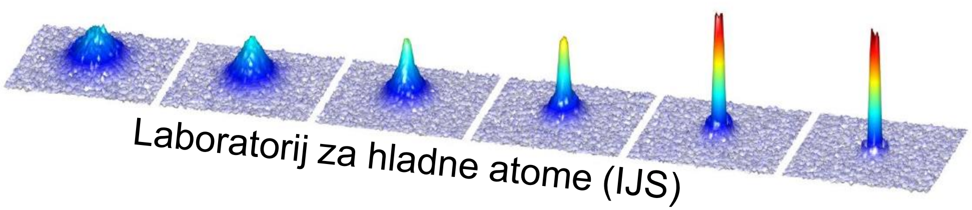
$$a = b \qquad \psi_{MB} = \psi_a(\vec{r}_1)\psi_a(\vec{r}_2) \qquad |\psi_{MB}|^2 = |\psi_a(\vec{r}_1)|^2|\psi_a(\vec{r}_2)|^2$$

- Kvantni (nerazločljivi) delci:

a) bozoni

$$\psi_b = \frac{1}{\sqrt{2}}\left[\psi_a(\vec{r}_1)\psi_b(\vec{r}_2) + \psi_a(\vec{r}_2)\psi_b(\vec{r}_1)\right]$$

$$a = b \qquad \psi_b = \sqrt{2}\psi_a(\vec{r}_1)\psi_a(\vec{r}_2) \qquad |\psi_b|^2 = 2|\psi_a(\vec{r}_1)|^2|\psi_a(\vec{r}_2)|^2 = 2|\psi_{MB}|^2$$



BOSE-EINSTEINOVA KONDENZACIJA

b) fermioni

$$\psi_f = \frac{1}{\sqrt{2}}\left[\psi_a(\vec{r}_1)\psi_b(\vec{r}_2) - \psi_a(\vec{r}_2)\psi_b(\vec{r}_1)\right]$$

$$a = b \qquad \psi_f = \sqrt{2}\left[\psi_a(\vec{r}_1)\psi_a(\vec{r}_2) - \psi_a(\vec{r}_2)\psi_a(\vec{r}_1)\right] = 0 \qquad |\psi_f|^2 = 0$$

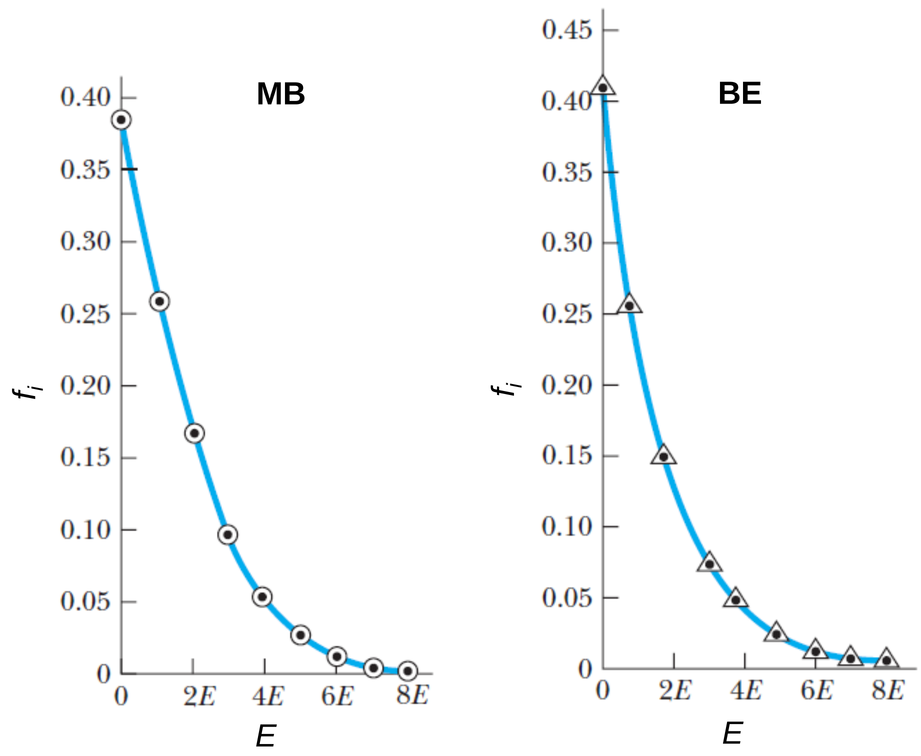
PAULIJEVO IZKLJUČITVENO NAČELO

SIMULACIJA

Vir: internet

8.2 Kvantna statistika

- *Primer*: 6 bozonov s skupno energijo 8*E*
- konfiguracija = mikrostanje
- Porazdelitvena funkcija: f_i

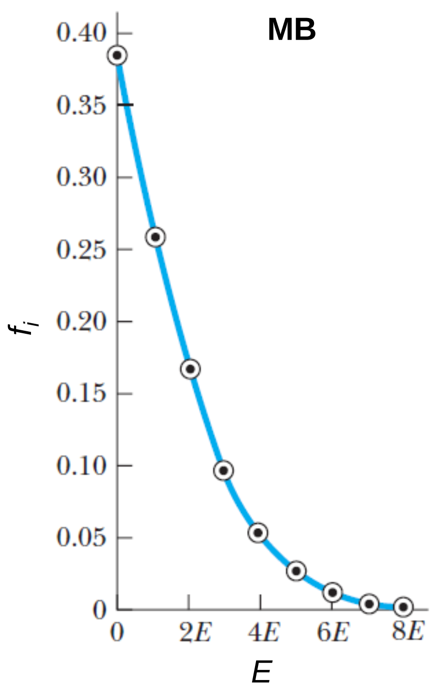


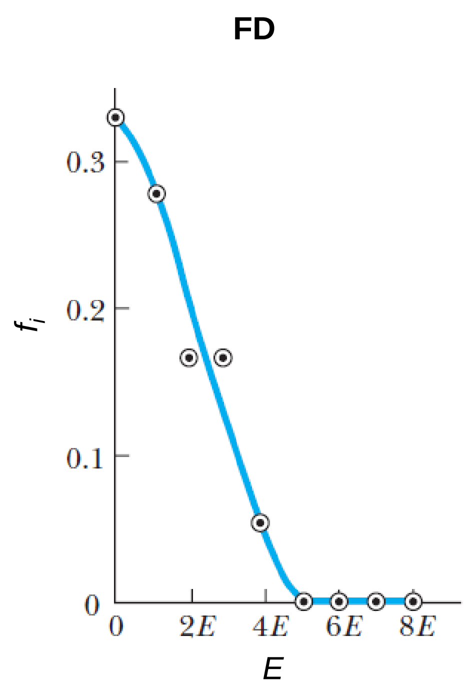
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

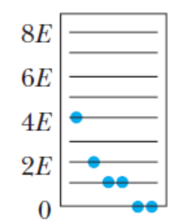
- *Primer*: 6 fermionov (spin 1/2) s skupno energijo 8*E*

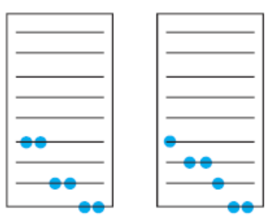
- konfiguracija = mikrostanje

- Porazdelitvena funkcija: f_i









Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

8.2 Kvantna statistika

- Bose-Einsteinova (BE) in Fermi-Diracova (FD) porazdelitev:
- Porazdelitvena funkcija (zvezna):

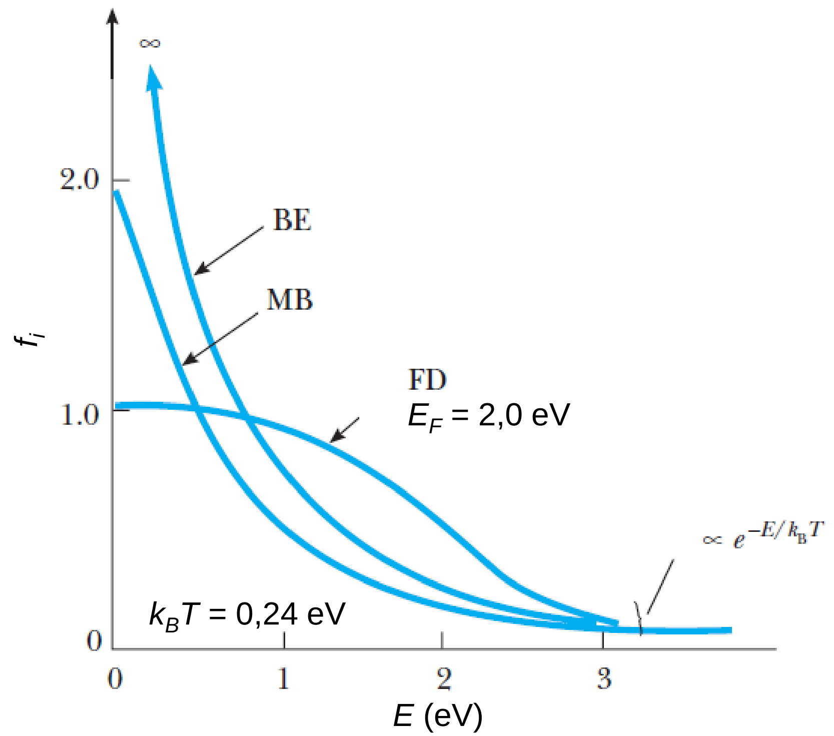
BOZONI

$$f_{BE}(E) = \frac{1}{B\mathrm{e}^{E/k_BT} - 1}$$

$$\frac{N}{V} = \int_0^\infty \frac{g(E)\mathrm{d}E}{B\mathrm{e}^{E/k_BT} - 1}$$

(št. delcev ni fiksno)

$$\frac{N}{V} = \int_0^\infty \frac{g(E)\mathrm{d}E}{\mathrm{e}^{E/k_BT} - 1}$$



FERMIONI

$$f_{FD}(E) = \frac{1}{F\mathrm{e}^{E/k_BT} + 1}$$

$$\frac{N}{V} = \int_0^\infty \frac{g(E)\mathrm{d}E}{F\mathrm{e}^{E/k_BT} + 1}$$

Fermijeva energija

$$F = \mathrm{e}^{-E_F/k_BT}$$

$$\frac{N}{V} = \int_0^\infty \frac{g(E)\mathrm{d}E}{\mathrm{e}^{(E-E_F)/k_BT} + 1}$$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

8.3 Primeri uporabe kvantne statistike

- Fermijev plin: elektroni (spin *S* = 1/2) v kovinah kot plin s Fermi-Diracovo statistiko:

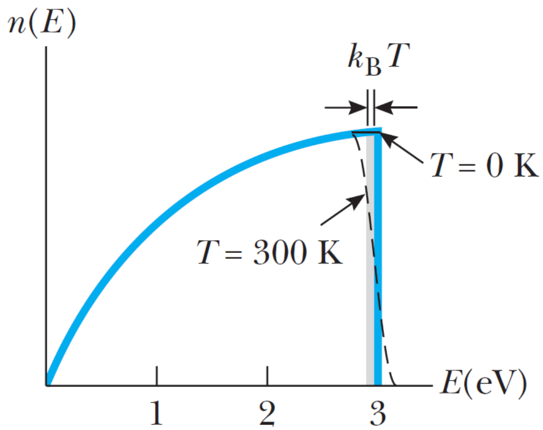
Št. zasedenih stanj:

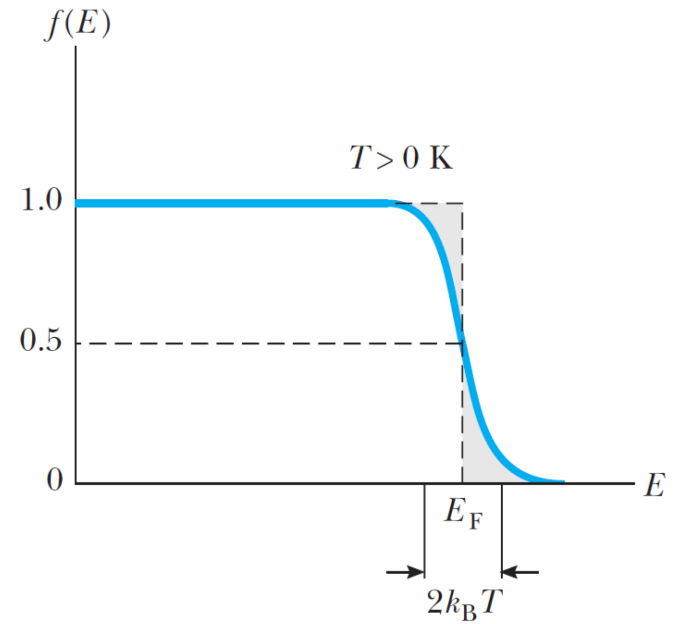
$$n(E)\mathrm{d}E = g(E) f_{FD}(E)\mathrm{d}E$$

$$f_{FD}(E) = \frac{1}{\mathrm{e}^{(E-E_F)/k_B T} + 1}$$

$$g(E)\mathrm{d}E = 4\pi\left(\frac{2m}{h^2}\right)^{3/2}\sqrt{E}\mathrm{d}E$$

$$\frac{N}{V} = \int_0^\infty 4\pi\left(\frac{2m}{h^2}\right)^{3/2}\frac{\sqrt{E}\mathrm{d}E}{\mathrm{e}^{(E-E_F)/k_B T} + 1}$$





$$E_F(T=0) = \frac{h^2}{2m}\left(\frac{3}{8\pi}\frac{N}{V}\right)^{2/3}$$

Fermijeva hitrost

$$v_F = \sqrt{\frac{2E_F}{m_e}}$$

Fermijeva temperatura

$$T_F = \frac{E_F}{k_B T}$$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

8.3 Primeri uporabe kvantne statistike

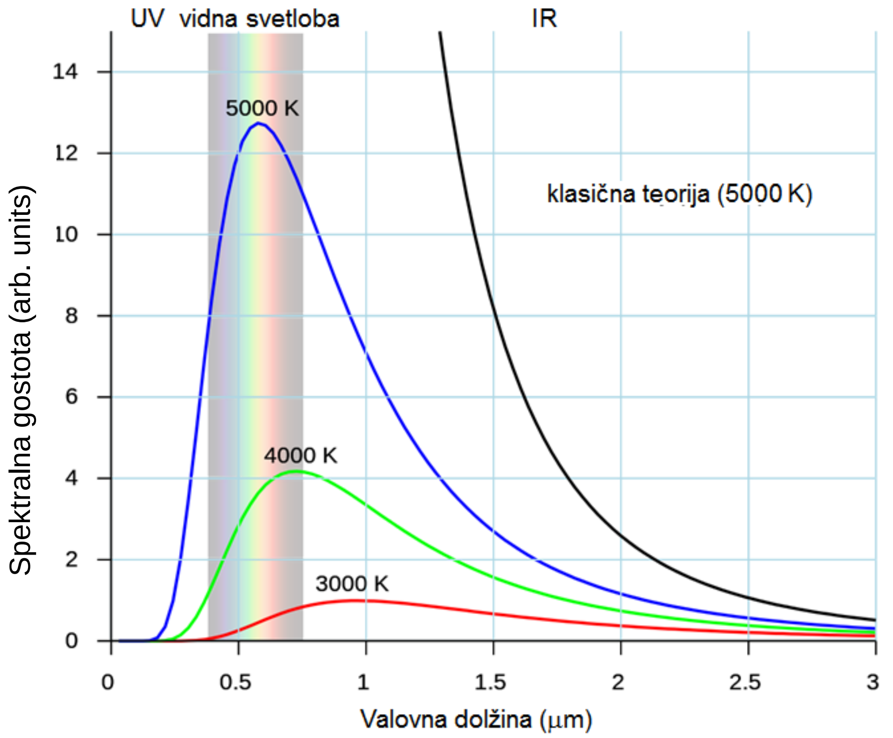
- Sevanje črnega telesa: fotoni (spin *S* = 1) kot plin z Bose-Einsteinovo statistiko:

Št. zasedenih stanj:

$$n(E)\mathrm{d}E = g(E)f_{BE}(E)\mathrm{d}E$$

$$f_{BE}(E) = \frac{1}{\mathrm{e}^{E/k_BT} - 1}$$

$$g(E)\mathrm{d}E = \frac{8\pi}{(hc)^3}E^2\mathrm{d}E$$



Gostota energijskega toka:

$$u(E)\mathrm{d}E = Eg(E)f_{BE}(E)\mathrm{d}E$$

$$\frac{\mathrm{d}j}{\mathrm{d}\nu} = \frac{c}{4}u(\nu) = \frac{2\pi h}{c^2}\frac{\nu^3}{\mathrm{e}^{h\nu/k_BT} - 1}$$

Vir: internet

8.3 Primeri uporabe kvantne statistike

- Bose-Einsteinova kondenzacija: plin bozonov s fiksnim številom delcev

Št. zasedenih stanj:

$$n(E)\mathrm{d}E = g(E) f_{BE}(E)\mathrm{d}E$$

$$f_{BE}(E) = \frac{1}{B\mathrm{e}^{E/k_BT} - 1}$$

$$g(E)\mathrm{d}E = 2\pi \left(\frac{2m}{h^2}\right)^{3/2} \sqrt{E}\mathrm{d}E$$

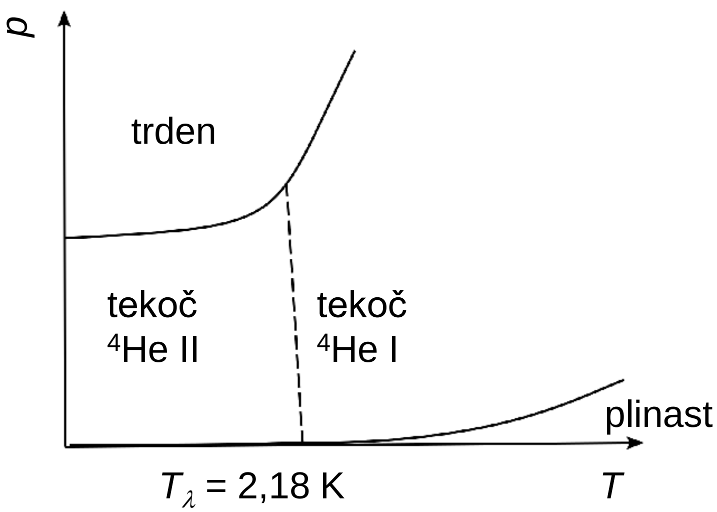
$$\frac{N}{V} = \frac{N_0}{V} + 2\pi \left(\frac{2m}{h^2}\right)^{3/2} \int_0^\infty \frac{\sqrt{E}\mathrm{d}E}{B\mathrm{e}^{E/k_BT} - 1}$$

$$N_0 = N - 2\pi V \left(\frac{2m}{h^2}\right)^{3/2} I(1)(k_bT)^{3/2}$$

$$I(1) = \int_0^\infty \frac{\sqrt{z}\mathrm{d}z}{\mathrm{e}^z - 1} = 2{,}6\frac{\sqrt{\pi}}{2}$$

Temperature prehoda:

$$T_{BE} = \left(\frac{N}{V}\frac{1}{2\pi I(1)}\right)^{2/3} \frac{h^2}{2mk_B}$$

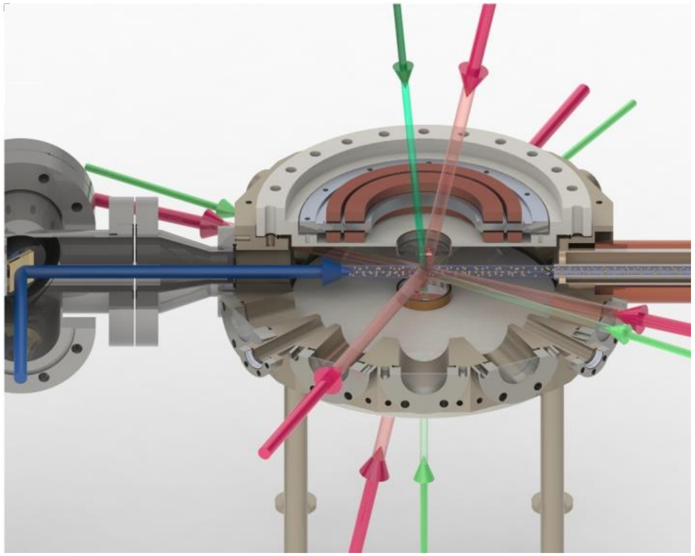


SIMULACIJA

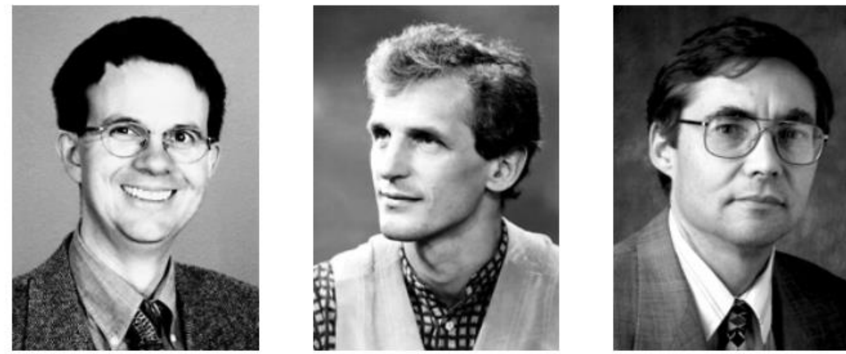
Vir: internet

8.3 Primeri uporabe kvantne statistike

- Bose-Einsteinova kondenzacija v eksperimentu s hladnimi atomi:



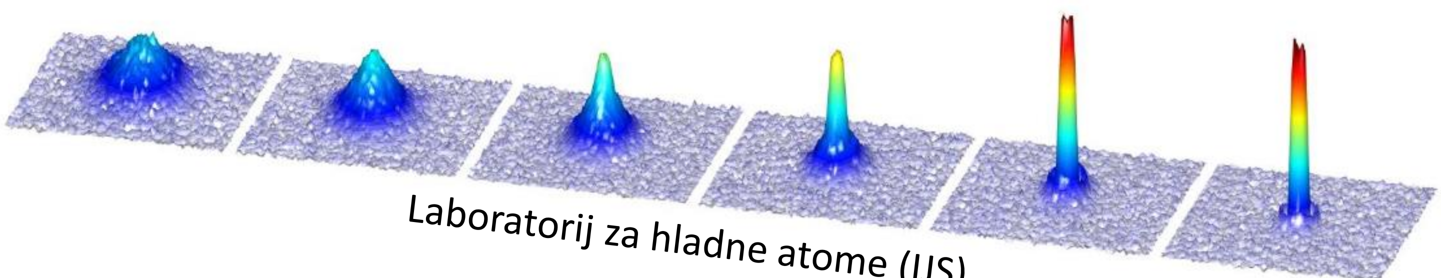
The Nobel Prize in Physics 2001



Eric A. Cornell	Wolfgang Ketterle	Carl E. Wieman
Prize share: 1/3	Prize share: 1/3	Prize share: 1/3

The Nobel Prize in Physics 2001 was awarded jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman *"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"*.

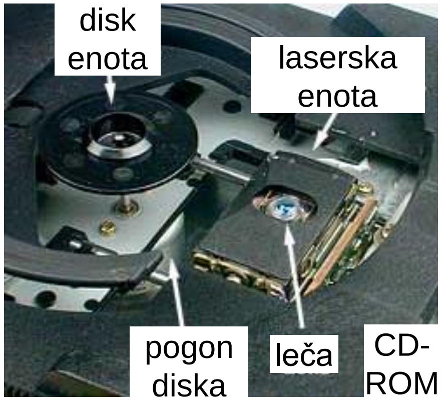
Porazdelitev hitrosti (BEC):



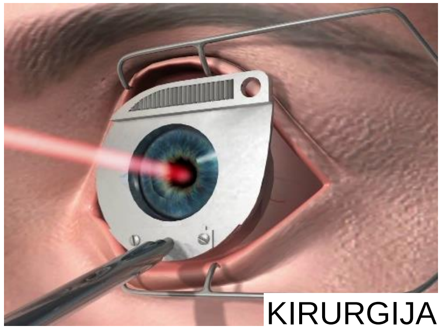
Vir: internet

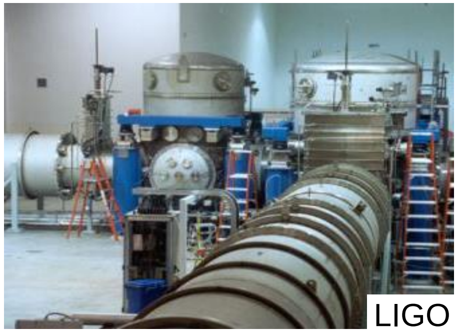
8.4 Laserji

➢ Širok spekter: SIMULACIJA



CNC





Vir: internet

The Nobel Prize in Physics 1964

Charles Hard Townes
Prize share: 1/2

Nicolay Gennadiyevich Basov
Prize share: 1/4

Aleksandr Mikhailovich Prokhorov
Prize share: 1/4

The Nobel Prize in Physics 1964 was divided, one half awarded to Charles Hard Townes, the other half jointly to Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prokhorov *"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"*.

Physikalische Zeitschrift **18**, 121 **1917**

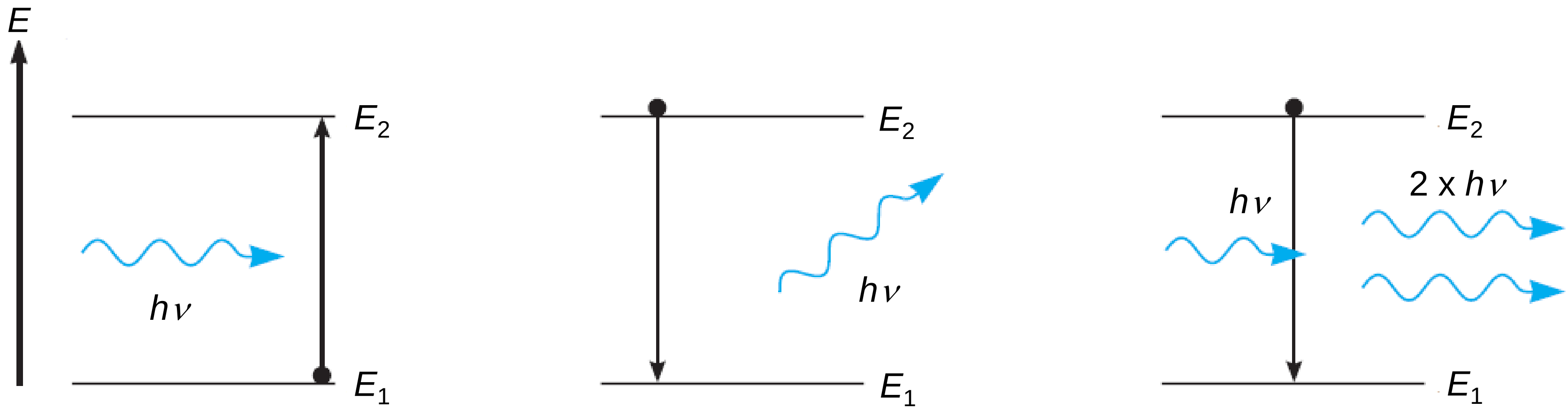
The Quantum Theory of Radiation

A. Einstein

(Received March, 1917)

8.4 Laserji

- Prehodi med nivoji: $h\nu = E_2 - E_1$



absorpcija | spontana emisija (nekoherentna) | stimulirana emisija (koherentna)

- Verjetnosti za prehod na časovno enoto:

$$w_{12}(\nu, T) = B_{12} u(\nu, T) \qquad w_{21}^{sp} = A_{21} \qquad w_{21}^{st}(\nu, T) = B_{21} u(\nu, T)$$

- Termično ravnovesje (dinamično):

$$\frac{N_2}{N_1} = e^{-h\nu(k_B T)} \qquad N_1 w_{12}(\nu, T) = N_2 \left[w_{21}^{sp} + w_{21}^{st}(\nu, T) \right]$$

$$u(\nu, T) = \frac{A_{21}}{B_{12} e^{h\nu(k_B T)} - B_{21}} = \frac{8\pi h}{c^3} \frac{\nu^3}{e^{h\nu(k_B T)} - 1}$$

$$B_{21} = B_{12} = B$$

$$A_{12} = \frac{8\pi h \nu^3}{c^3}$$

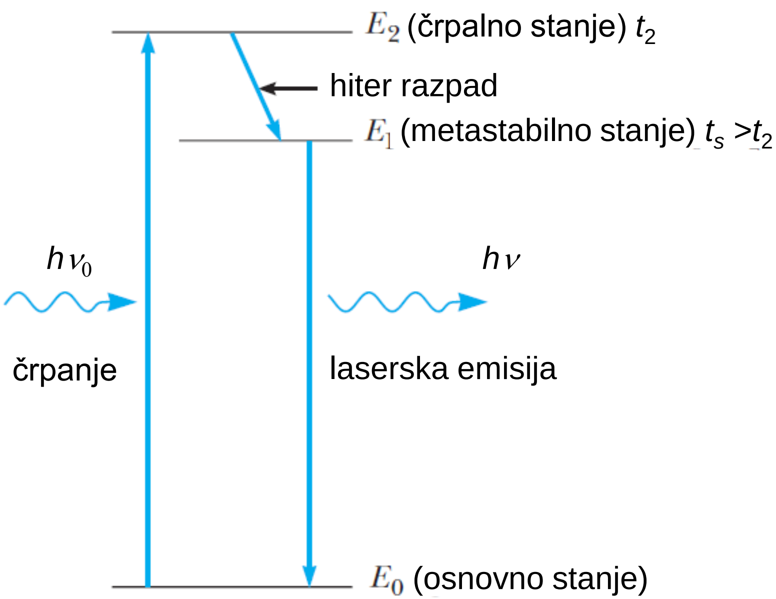
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

8.4 Laserji

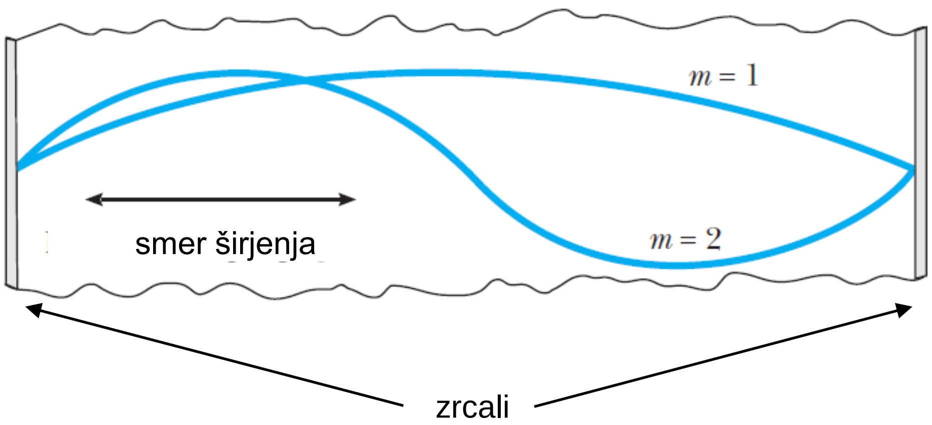
- Osnovni principi delovanja:

1. Inverzna populacija: $N_2 > N_1 \quad \Rightarrow \quad N_2 w_{21}^{st}(\nu, T) > N_1 w_{12}(\nu, T)$ (ojačitev svetlobe = „lasing“)

2. Laserski medij:



3. Optični resonator



- Osnovne lastnosti:
  - monokromatičnost
  - velika intenziteta
  - prostorska koherenca
  - majhna divergenca

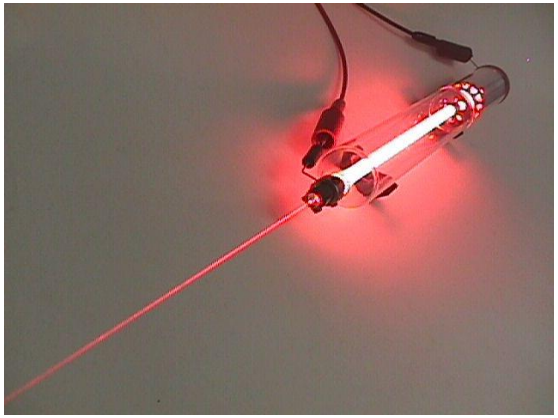
SIMULACIJA

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

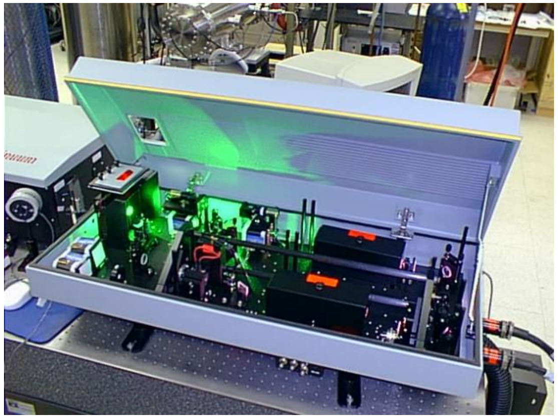
8.4 Laserji

- Tipi laserjev:

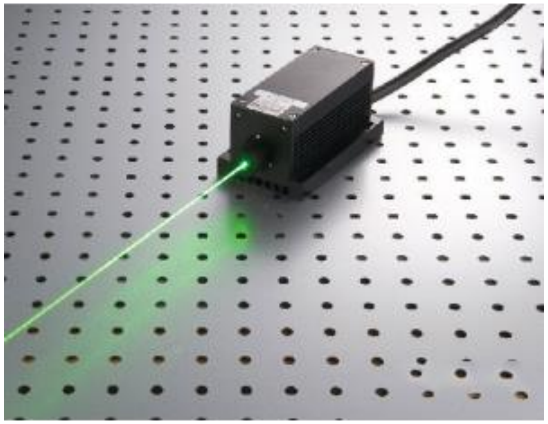
1. PLINSKI (He-Ne)



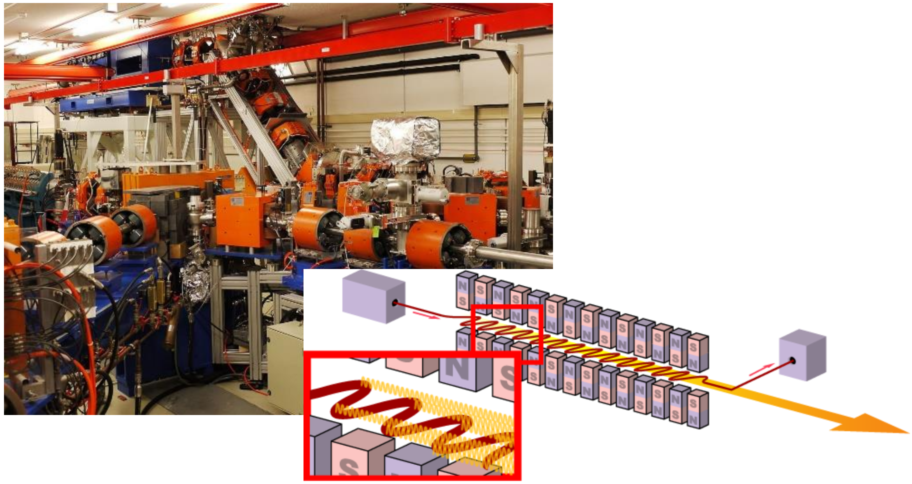
2. TRDNI KRISTALNI (Nd: YAG)



3. POLPREVODNIŠKI



4. PROSTO-ELEKTRONSKI



Vir: internet

Univerza v Ljubljani
Fakulteta za matematiko in fiziko

MODERNA FIZIKA

Trdna snov

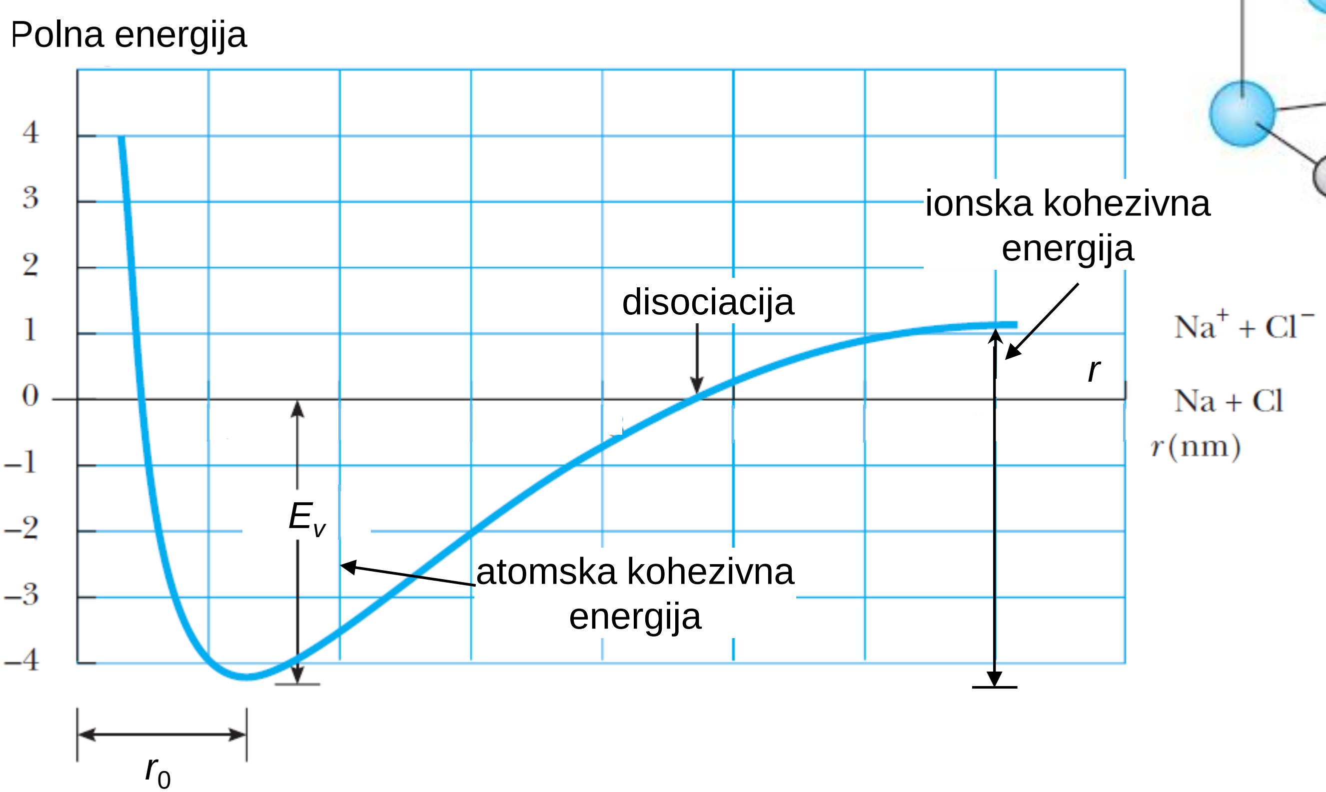
Andrej Zorko
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

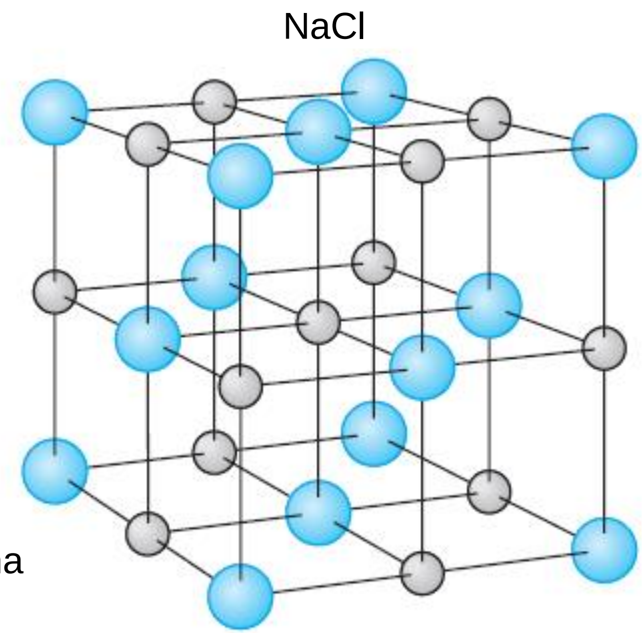
9.1 Povezovanje atomov v trdni snovi

1. Ionski kristali:

$$U(r) = -\alpha \frac{e^2}{4\pi\epsilon_0 r} + \frac{B}{r^m} + E_{ion} - E_{af}$$

Madelungova konstanta: $\alpha = 6 \times 1 - 12 \times \frac{1}{\sqrt{2}} + 8 \times \frac{1}{\sqrt{3}} - \dots$

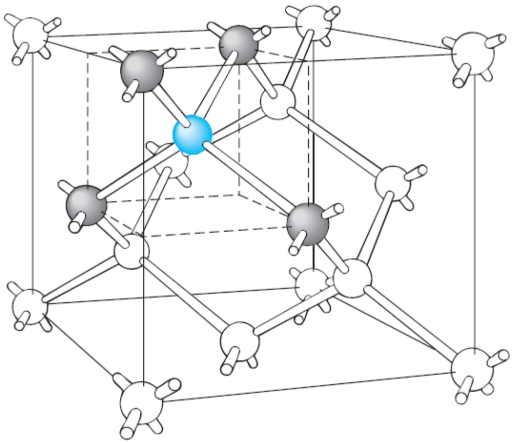




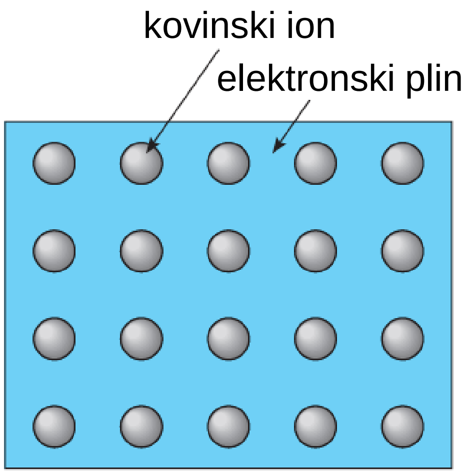
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

9.1 Povezovanje atomov v trdni snovi

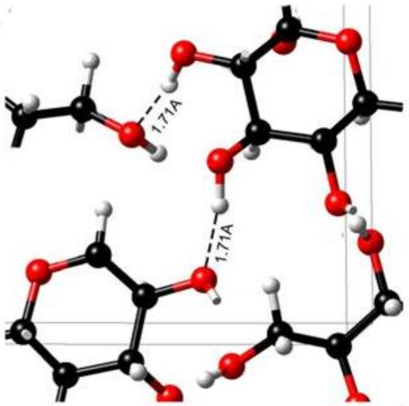
2. Kovalentni kristali (diamant):



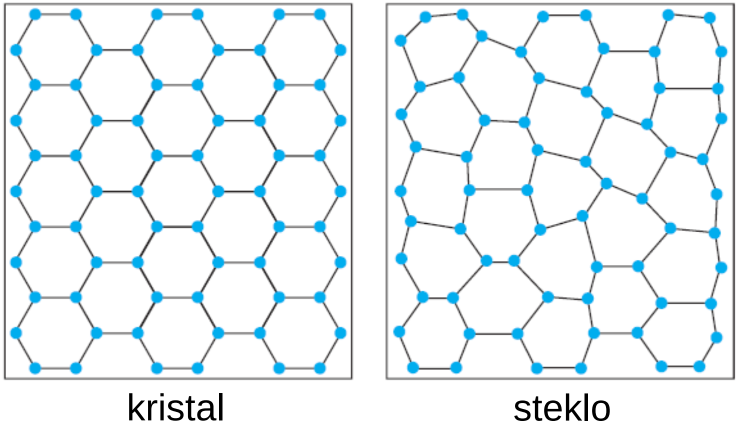
3. Kovinski kristali (Cu, Au, Na,…):



4. Molekularni kristali (kristal sladkorja):



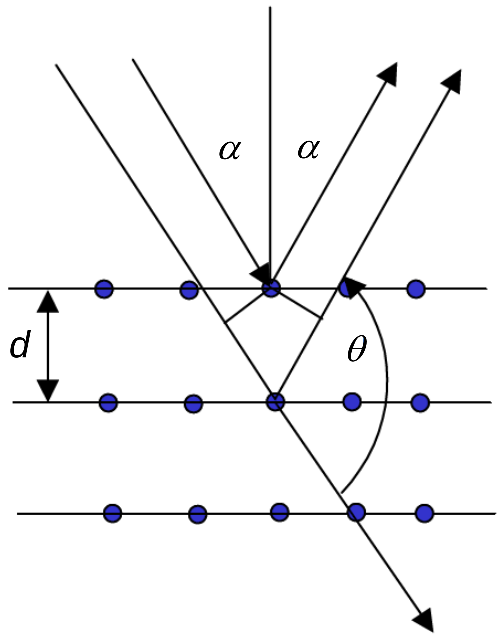
5. Amorfne snovi:



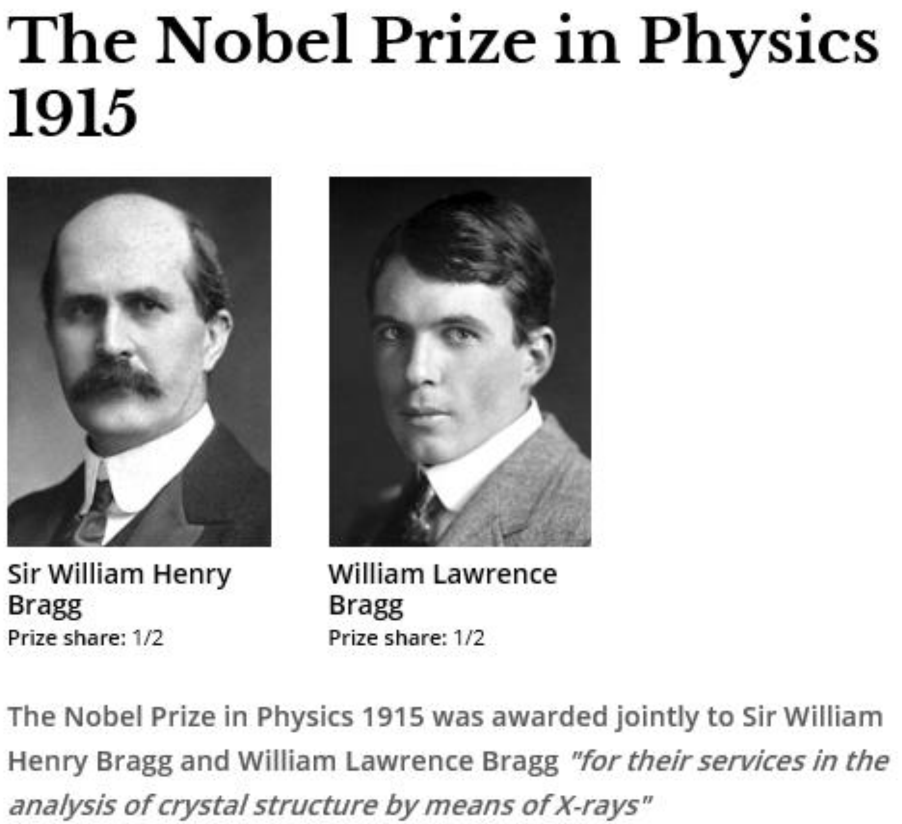
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

9.2 Določanje kristalne strukture

- Braggov uklon:



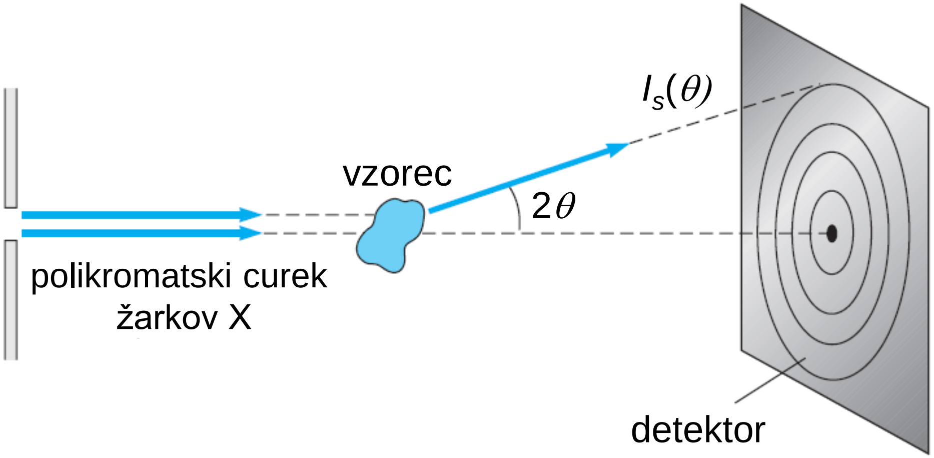
$$2d\cos\alpha = n\lambda \qquad 2d\sin\frac{\theta}{2} = n\lambda$$



Vir: internet

9.2 Določanje kristalne strukture

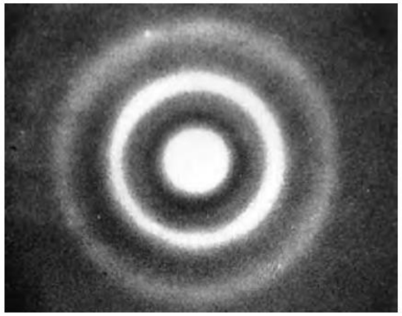
➢ Lauejeva metoda merjenja:



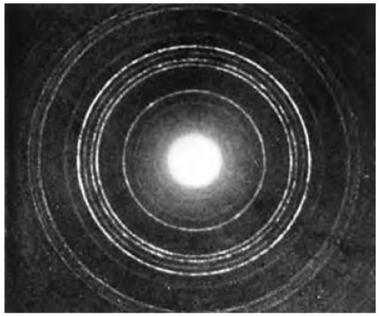
The Nobel Prize in Physics 1914

Max von Laue
Prize share: 1/1

The Nobel Prize in Physics 1914 was awarded to Max von Laue *"for his discovery of the diffraction of X-rays by crystals"*.



amorfni Fe



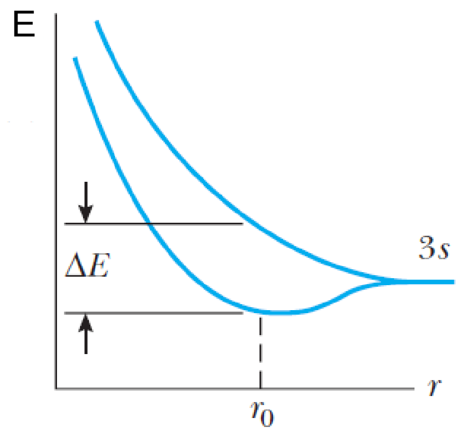
kristal Fe

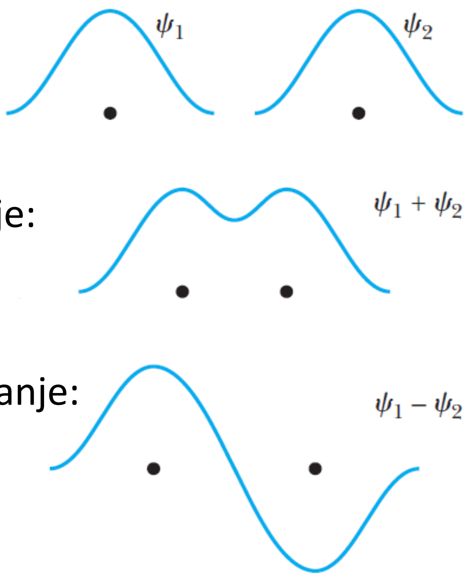
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

9.3 Pasovna struktura elektronskih stanj v kristalih

- Tvorba elektronskih pasov:

2 atoma:

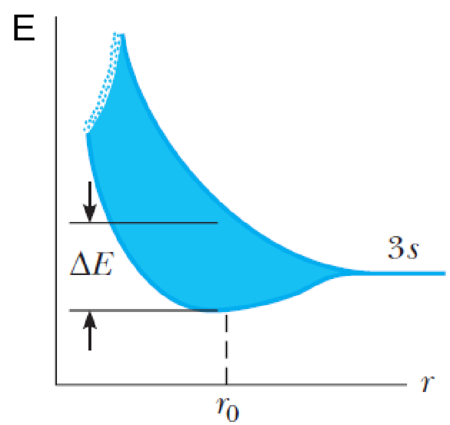




vezano stanje:

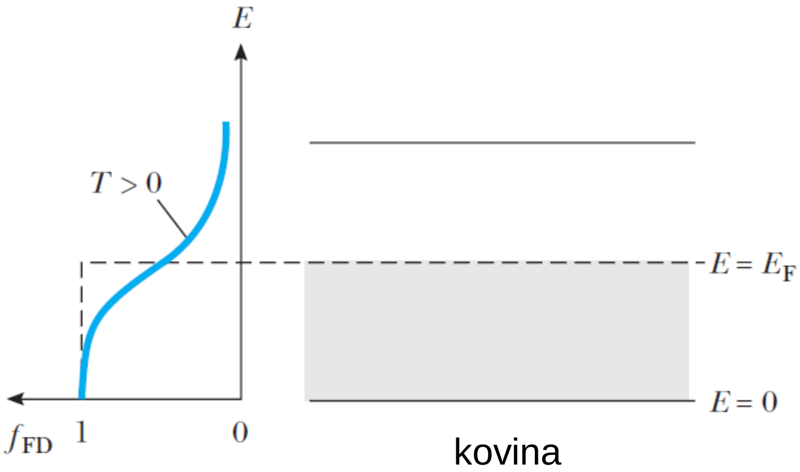
nevezano stanje:

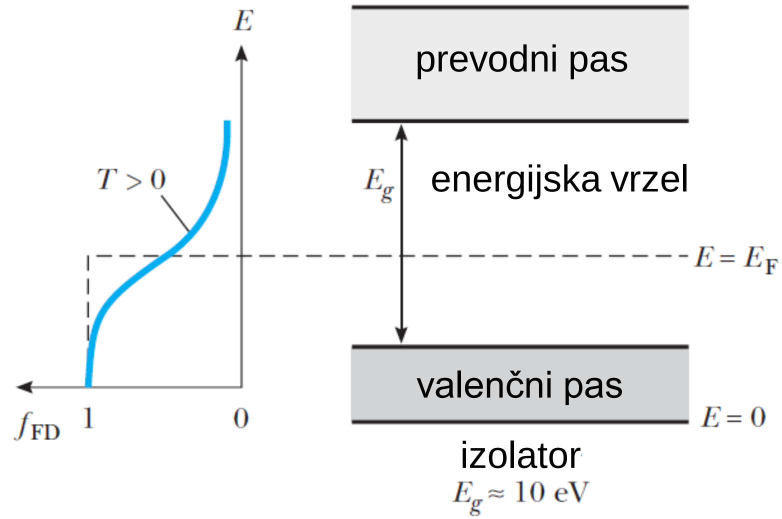
N atomov:

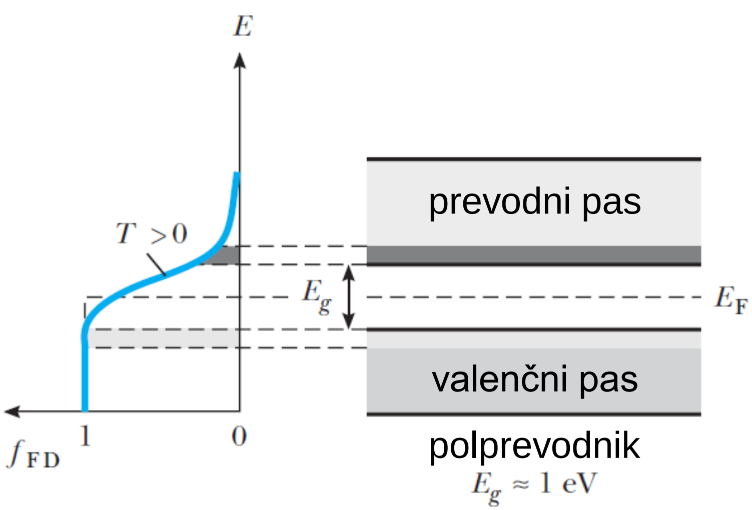


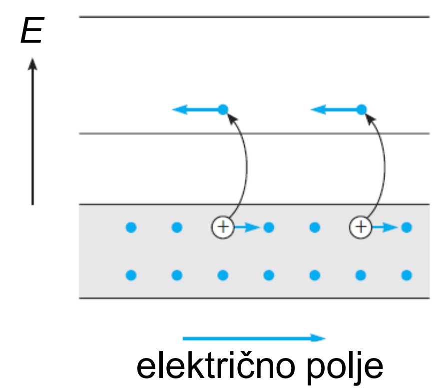
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

- Električna prevodnost:



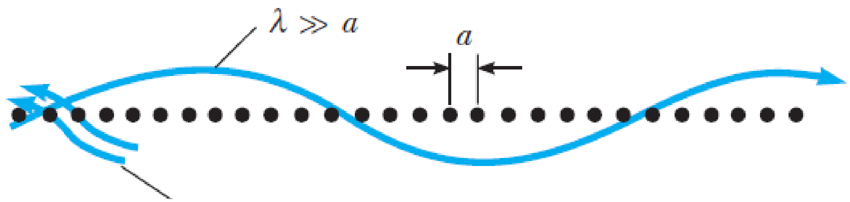


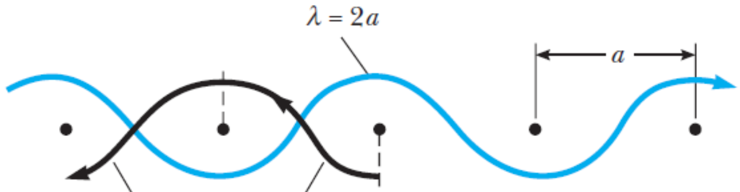




Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

- Efekt periodičnega potenciala:





- Konstruktivna interferenca odbitih valov: $2a = n\lambda \quad \Rightarrow \quad k_n = \frac{\pi}{a} n$

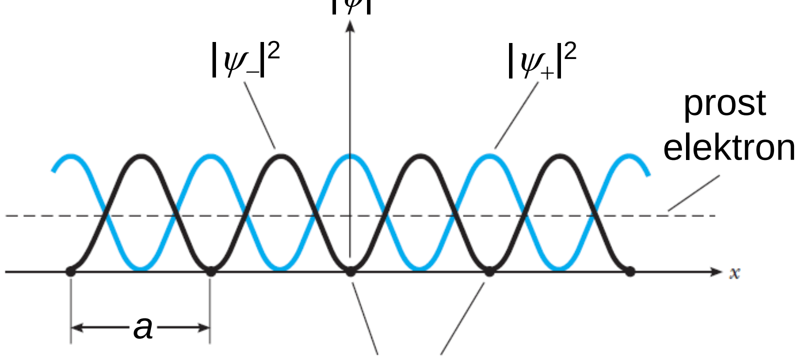
$$\psi_+ = A\left[\mathrm{e}^{i(kx-\omega t)} + \mathrm{e}^{i(-kx-\omega t)}\right]$$

$$\psi_- = A\left[\mathrm{e}^{i(kx-\omega t)} - \mathrm{e}^{i(-kx-\omega t)}\right]$$

$$k = \frac{\pi}{a}$$

$$|\psi_+|^2 = 4|A|^2 \cos^2 \frac{\pi x}{a}$$

$$|\psi_-|^2 = 4|A|^2 \sin^2 \frac{\pi x}{a}$$



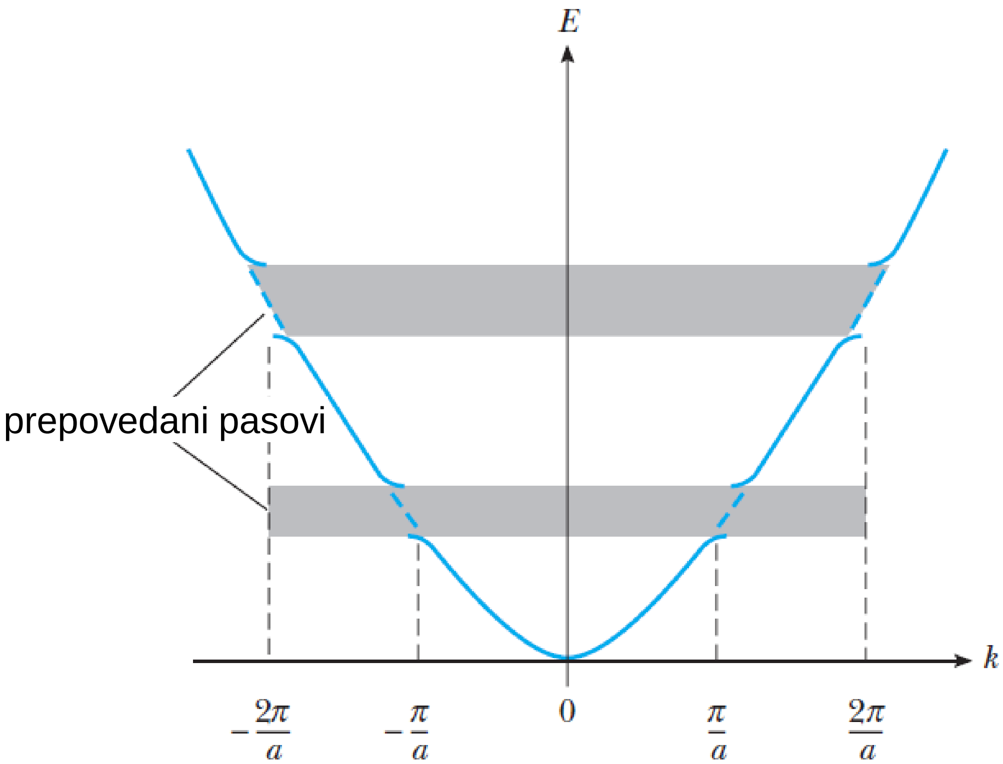
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

9.3 Pasovna struktura elektronskih stanj v kristalih

- Efekt periodičnega potenciala:

$$E_p = \frac{\hbar^2 k^2}{2m}$$

$$k_n = \frac{\pi}{a} n \qquad E_+ < E_p < E_-$$

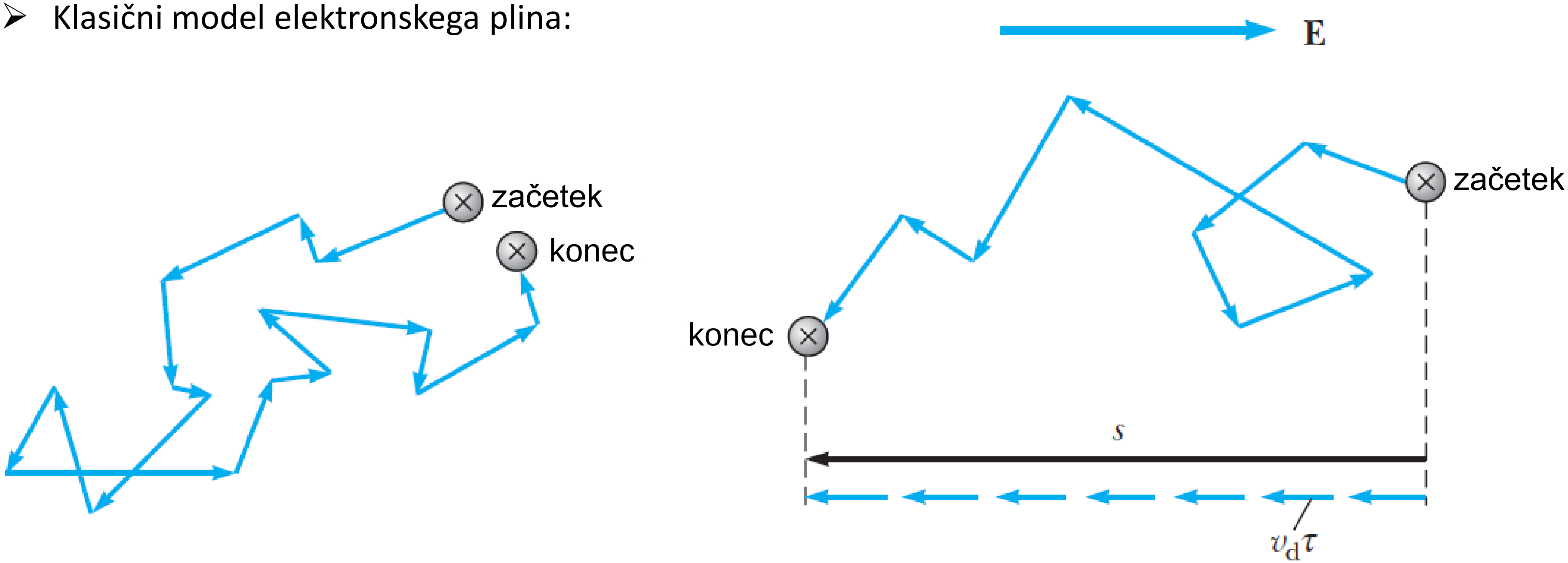


SIMULACIJA

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

9.4 Drudejev model elektronov v kovini

- Klasični model elektronskega plina:

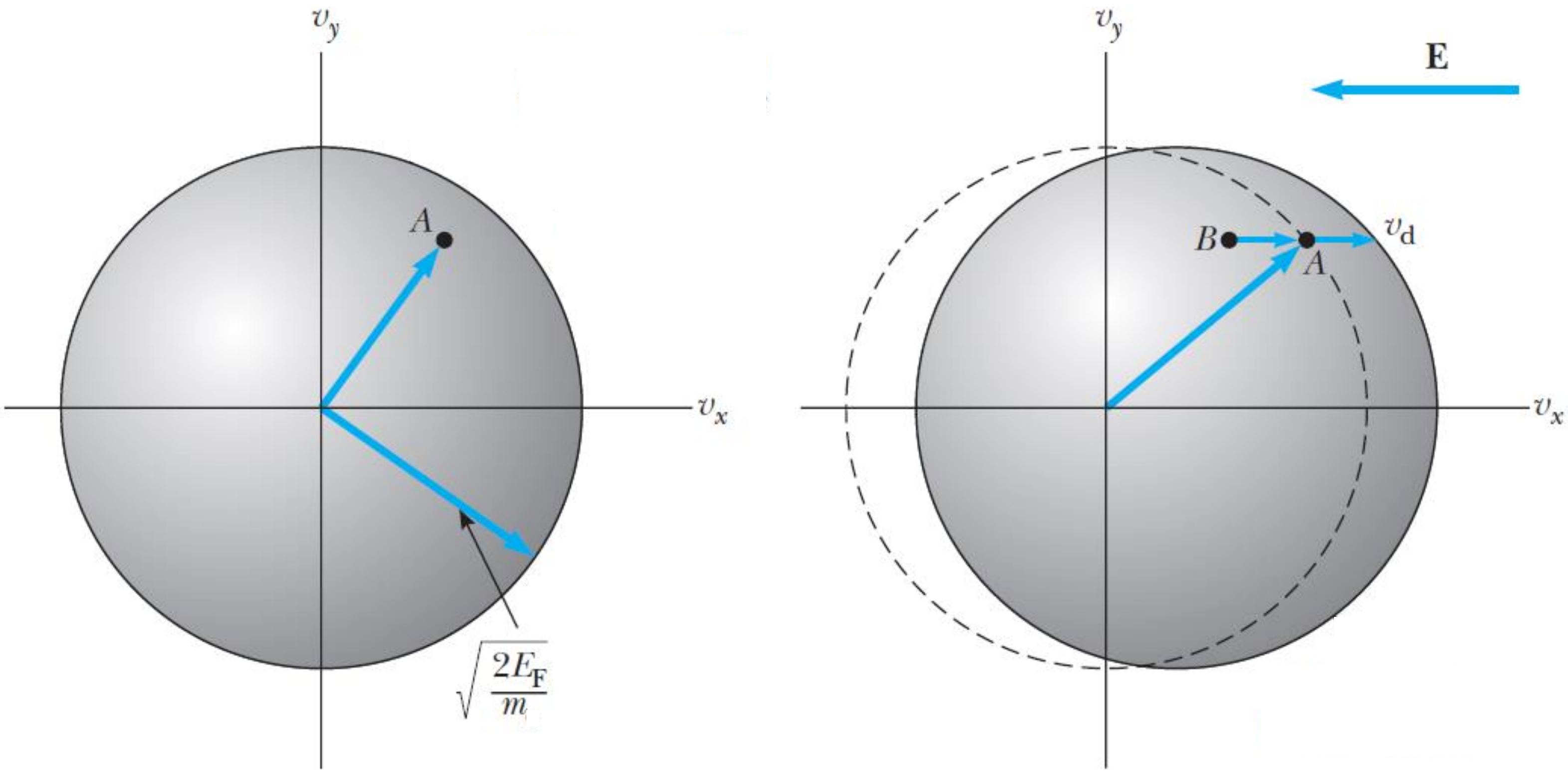


- termična hitrost: $v_t = \left(\frac{3k_BT}{m}\right)^{1/2}$
- povprečna prosta pot: $L = v_t\tau$
- povpečna hitrost v el. polju: $v_d = \frac{eE}{m}\tau$
- Ohmov zakon: $j = \sigma E$ $\sigma = \frac{ne^2\tau}{m} = \frac{ne^2L}{mv_t}$

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

9.5 Model Fermijevega plina

- Kvantni model elektronskega plina (Fermi-Diracova porazdelitev):



centrirana Fermijeva sfera

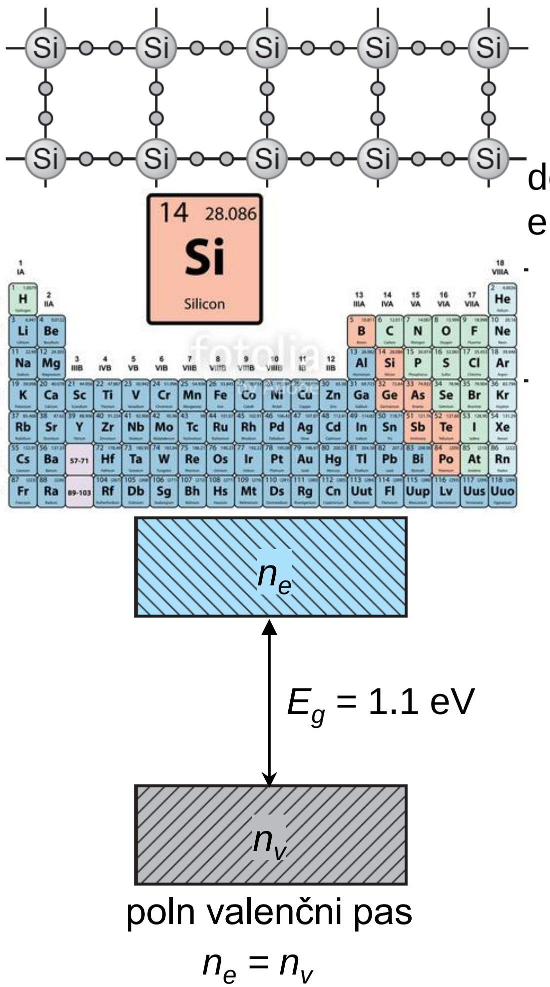
premaknjena Fermijeva sfera

- Fermijeva hitrost: $L = v_F \tau$ $\qquad \sigma = \frac{ne^2\tau}{m} = \frac{ne^2 L}{m v_F}$

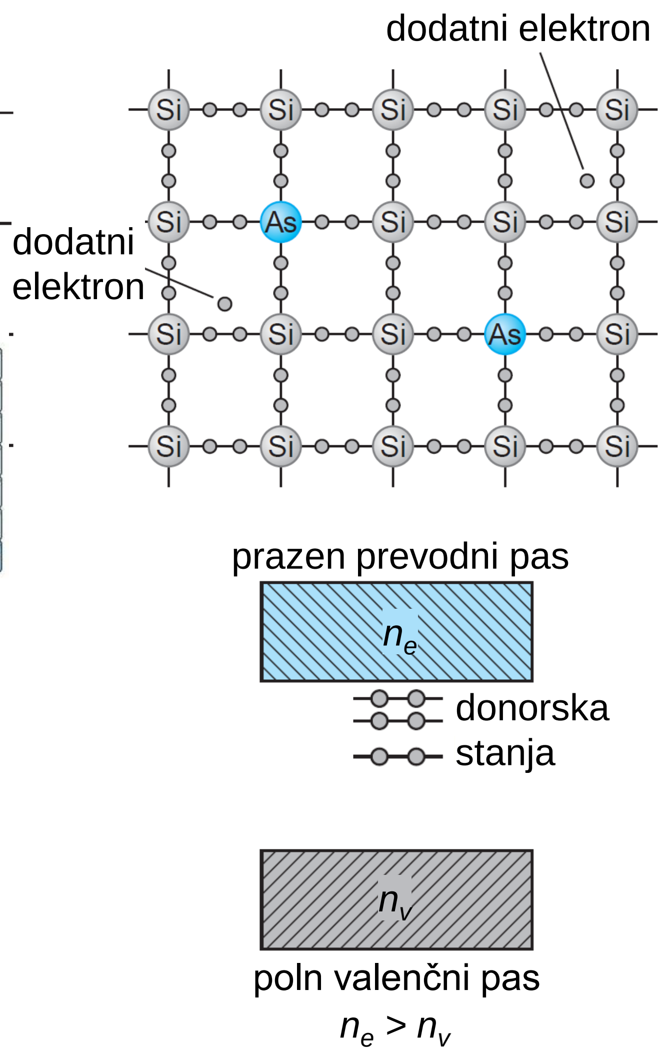
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

9.6 Čisti in dopirani polprevodniki

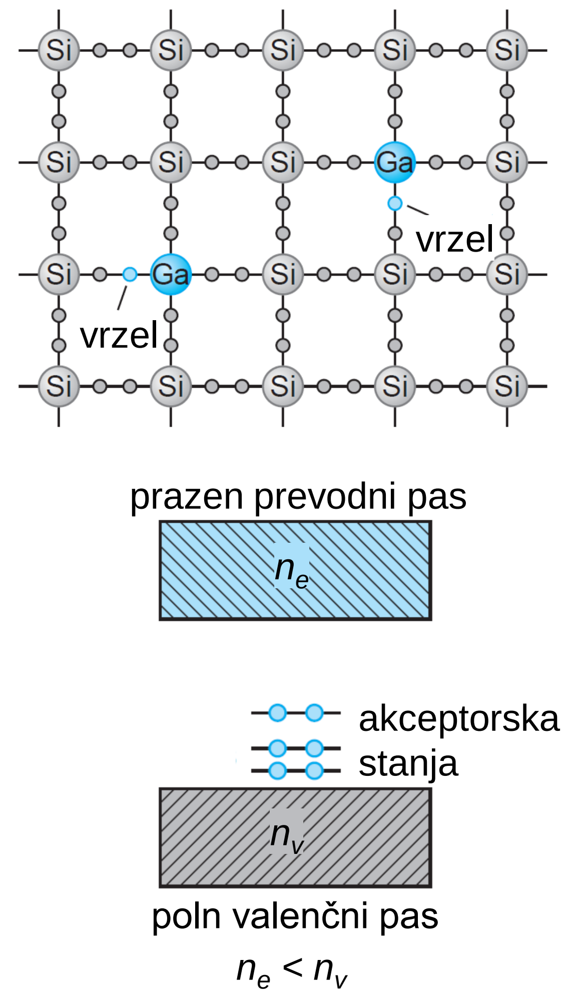
- Čisti polprevodnik:



- *N*-dopiran polprevodnik:



- *P*-dopiran polprevodnik:



Vir: povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

9.6 Čisti in dopirani polprevodniki

Čisti polprevodnik:

- Gostota elektronov v prevodnem pasu:

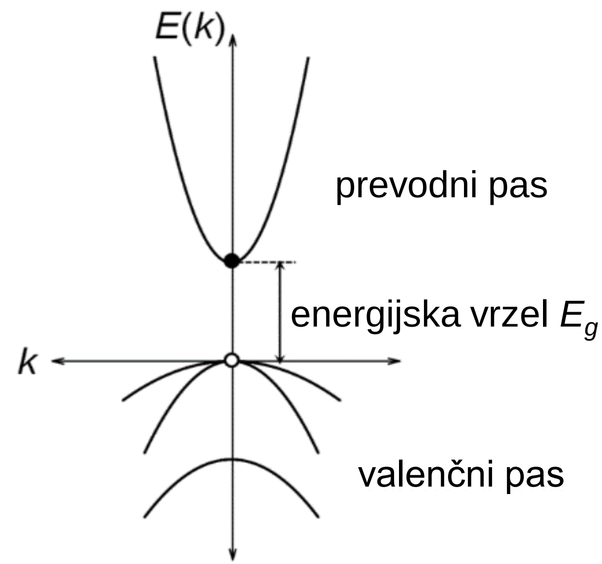
$$n_e = \int_{E_g}^{\infty} f_{FD}\, g(E)\mathrm{d}E$$
$$= 4\pi\left(\frac{2m_e}{h^2}\right)^{3/2}\int_{E_g}^{\infty}\frac{1}{\mathrm{e}^{(E-E_F)/k_BT}+1}\sqrt{E-E_g}\mathrm{d}E$$
$$= B_e(k_BT)^{3/2}\mathrm{e}^{-(E_g-E_F)/k_BT}$$

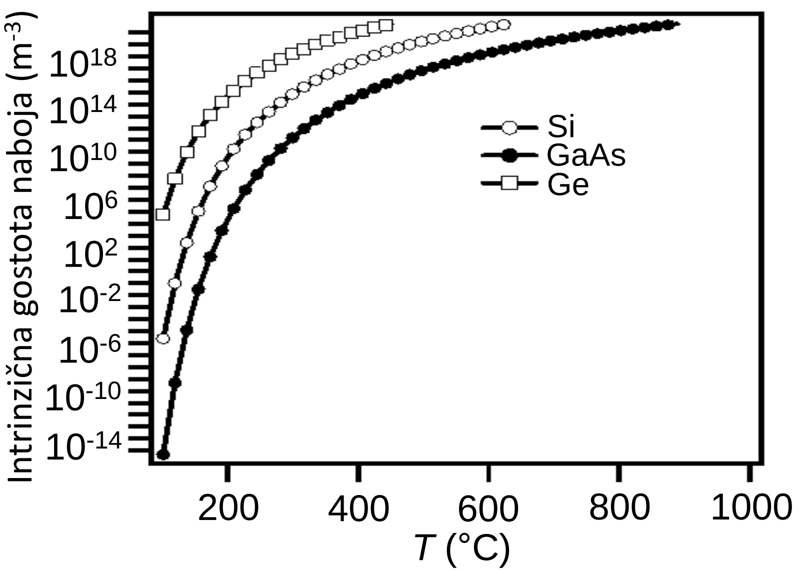
$$B_e = 2\left(\frac{2\pi m_e}{h^2}\right)^{3/2}$$

- Gostota vrzeli v valenčnem pasu:

$$n_v = \frac{N}{V} - \int_{-\infty}^{0} f_{FD}\, g(E)\mathrm{d}E$$
$$= 4\pi\left(\frac{2m_v}{h^2}\right)^{3/2}\int_{-\infty}^{0}\frac{1}{\mathrm{e}^{-(E-E_F)/k_BT}+1}\sqrt{-E}\mathrm{d}E$$
$$= B_v(k_BT)^{3/2}\mathrm{e}^{-E_F/k_BT}$$

$$B_v = 2\left(\frac{2\pi m_v}{h^2}\right)^{3/2}$$





Vir: internet

Čisti polprevodnik:

- Fermijeva energija:

$$n_e = n_v \quad \Rightarrow \quad E_F = \frac{E_g}{2} + \frac{3}{4} k_B T \ln \frac{m_v}{m_e}$$

- Efektivna gostota stanj:

$$n_e n_v = n_0^2 \mathrm{e}^{-E_g/k_B T}$$

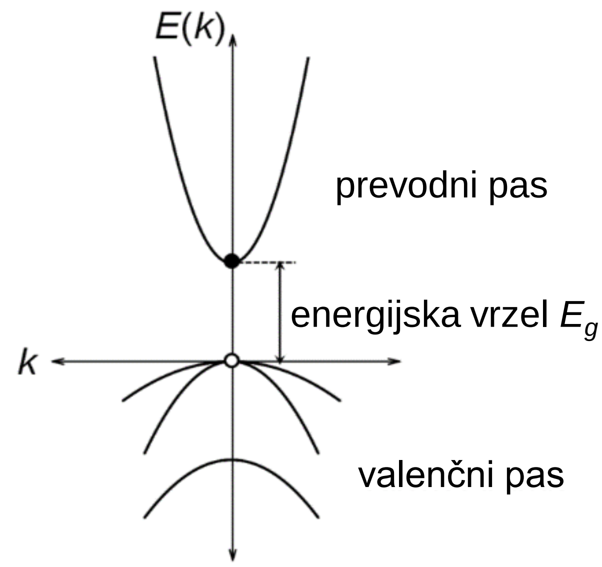
$$n_0 = 2 \left(\frac{2\pi \sqrt{m_e m_v} k_B T}{h^2} \right)^{3/2}$$

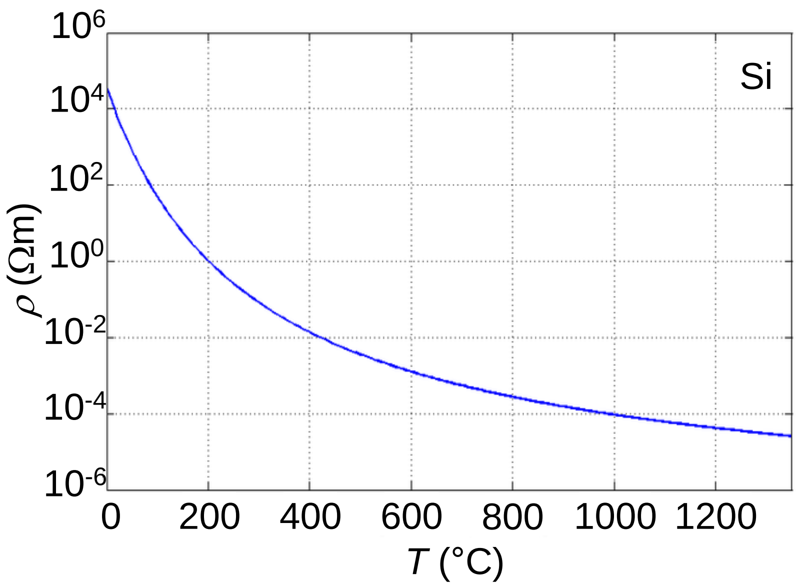
- Prevajanje električnega toka:

$$\beta = \frac{\langle v \rangle}{E}$$

$$j = e_0 (n_e \beta_e + n_v \beta_v) E$$

$$j = \sigma E = \frac{E}{\rho}$$





Vir: internet

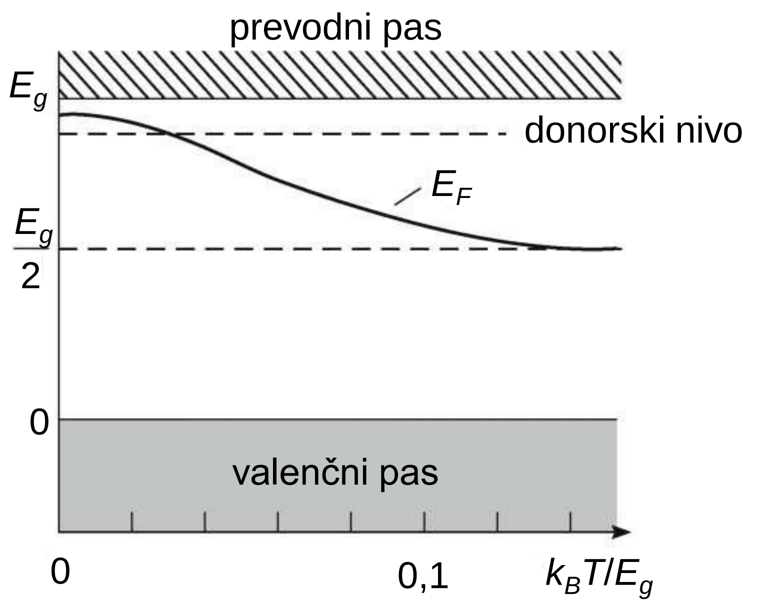
9.6 Čisti in dopirani polprevodniki

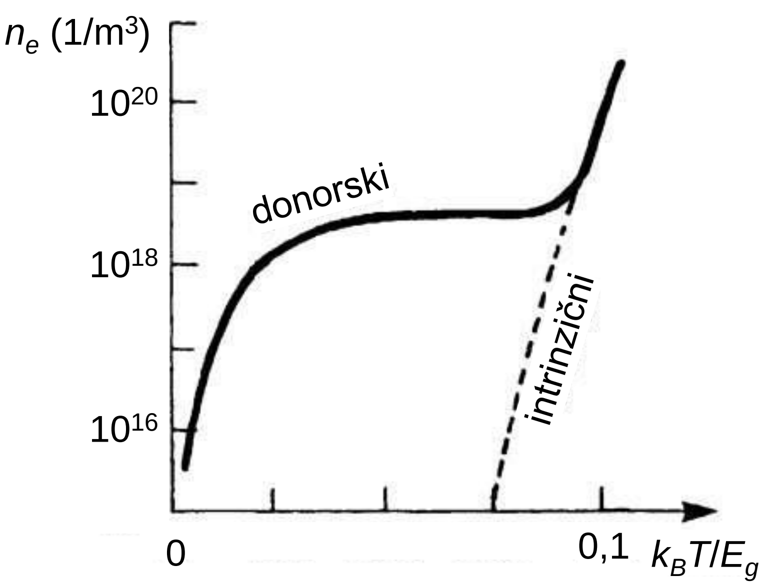
Dopiran polprevodnik:

$$n_e n_v = n_0^2 \mathrm{e}^{-E_g/k_B T}$$

$$n_0 = 2\left(\frac{2\pi\sqrt{m_e m_v}k_B T}{h^2}\right)^{3/2}$$

- tip *n*: $n_e = n_v + n_d[1 - f(E_g - E_d)]$

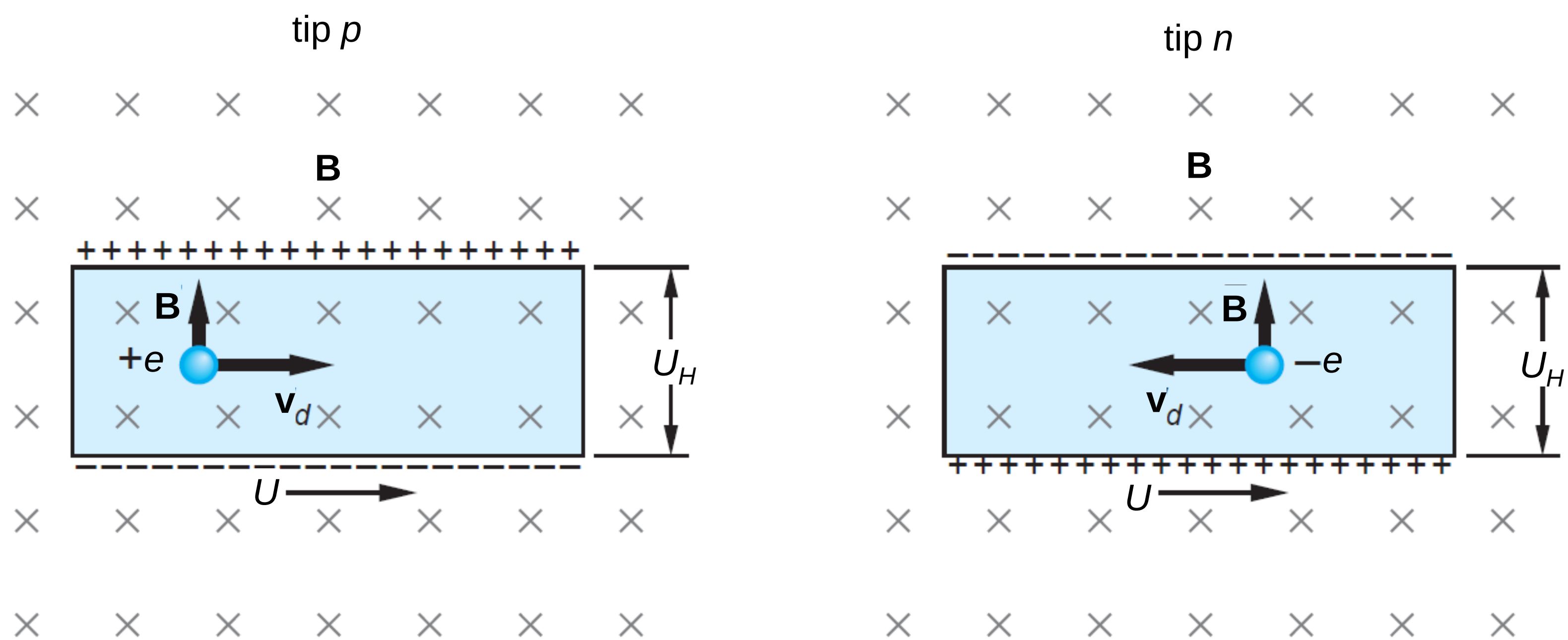




Vir: internet

9.6 Čisti in dopirani polprevodniki

- Meritev večinskih nosilcev naboja: Hallov pojav

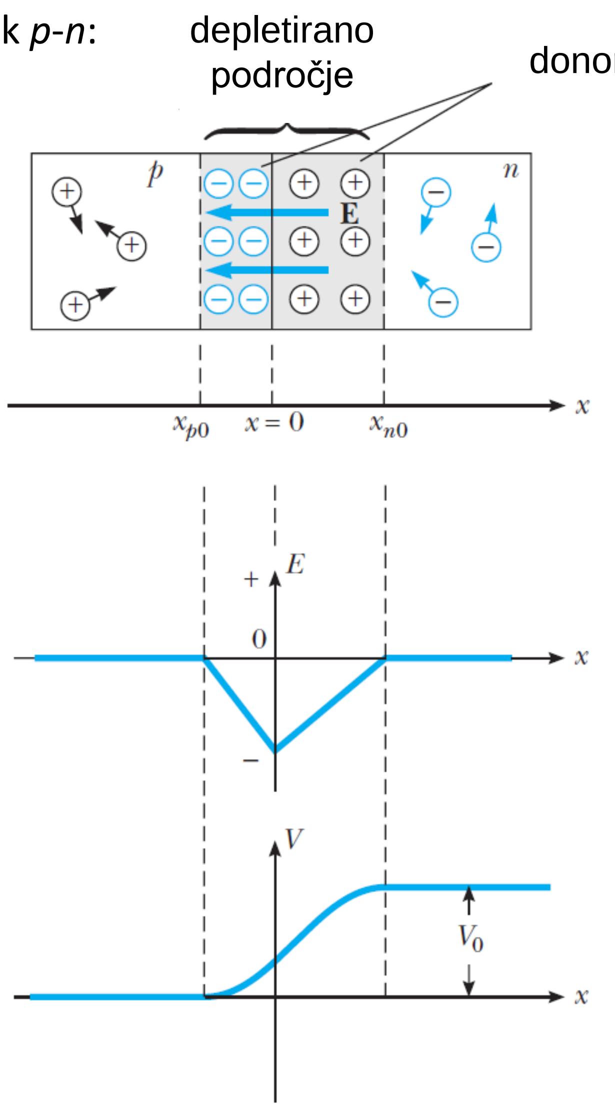


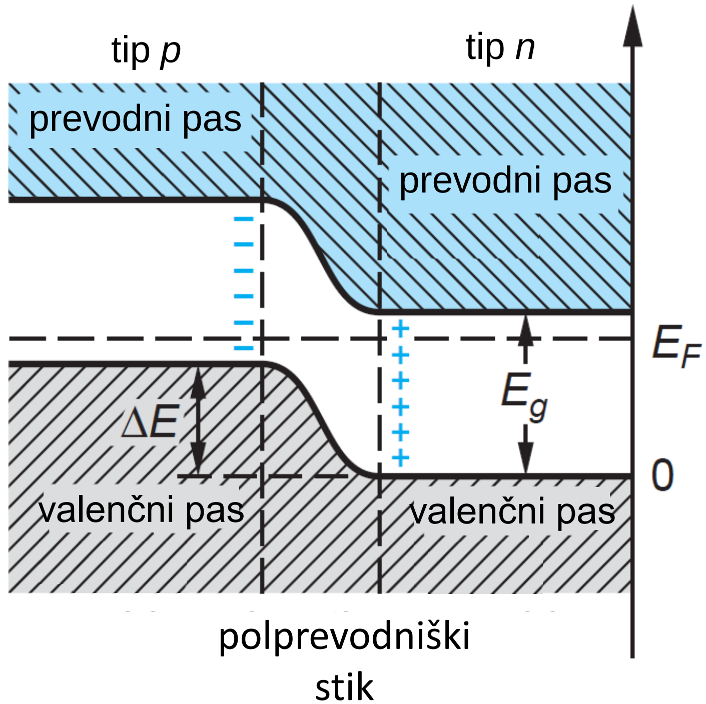
$$eE_H = e\frac{U_H}{a} = e\langle v\rangle B = \frac{j}{n}B = \frac{\sigma U}{cn}B$$

Vir: povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

9.7 Stik *p-n* in polprevodniške naprave

- Stik *p-n*:





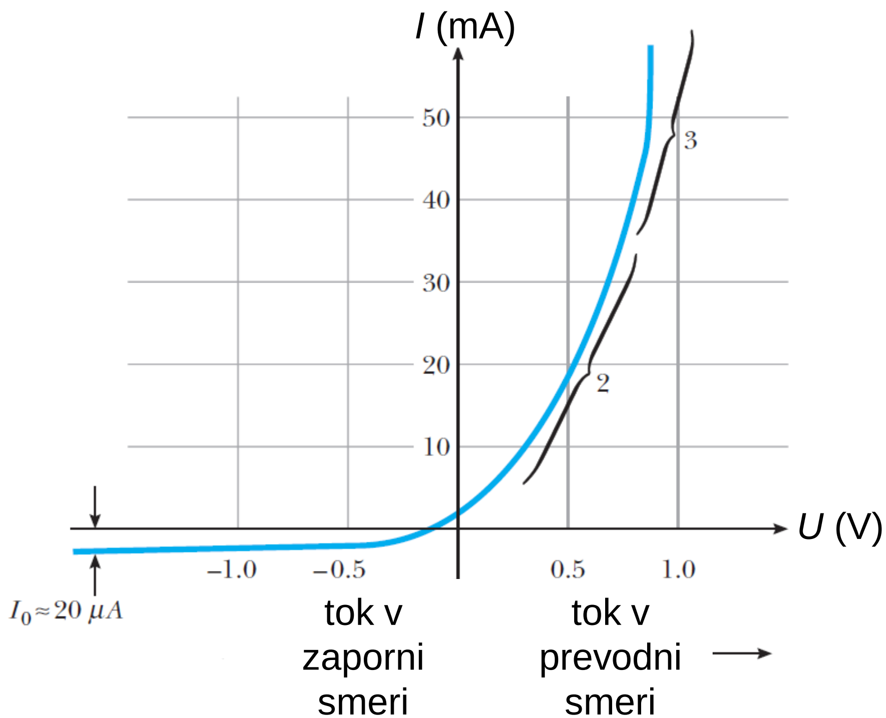
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

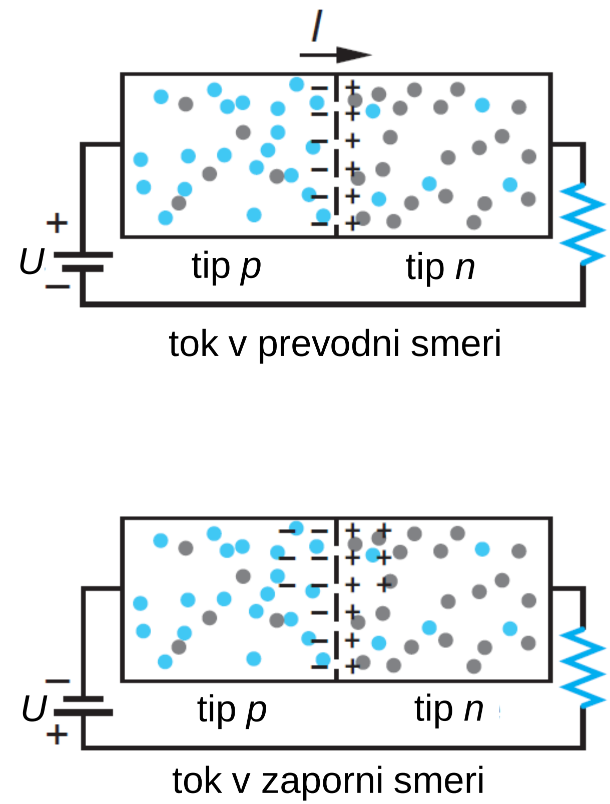
9.7 Stik *p-n* in polprevodniške naprave

➢ Polprevodniške naprave:

1. Usmerniška dioda:

$$I = I_0(e^{eU/K_BT} - 1)$$



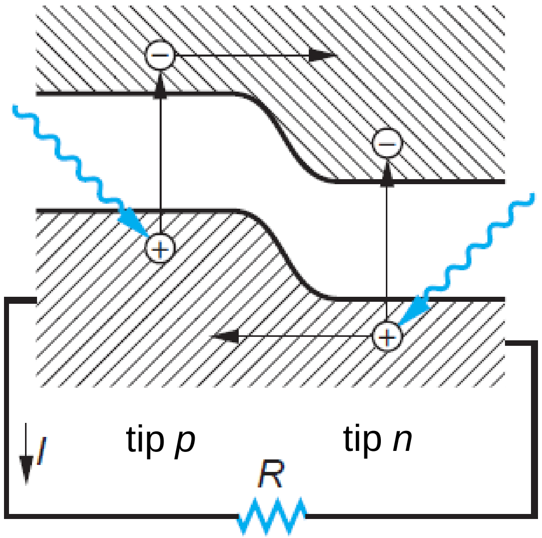


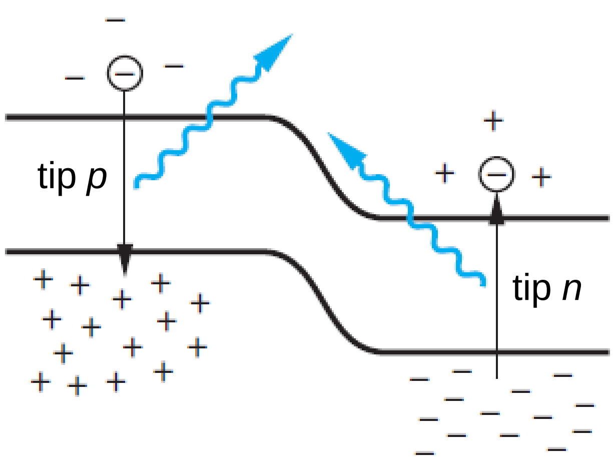
SIMULACIJA

Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

9.7 Stik *p-n* in polprevodniške naprave

2. Solarna celica in LED:





The Nobel Prize in Physics 2014

Photo: A. Mahmoud
Isamu Akasaki
Prize share: 1/3

Photo: A. Mahmoud
Hiroshi Amano
Prize share: 1/3

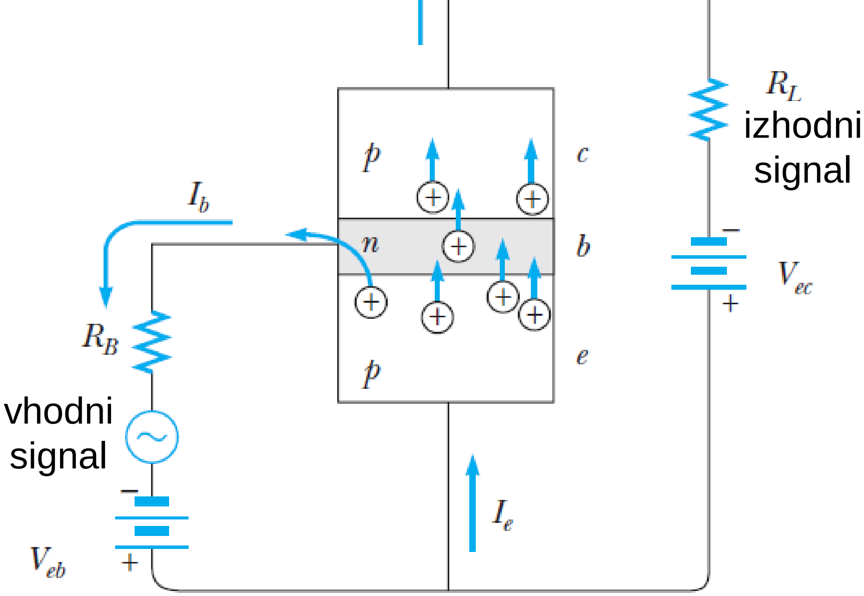
Photo: A. Mahmoud
Shuji Nakamura
Prize share: 1/3

The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura *"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"*.

Vir: internet; povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

9.7 Stik *p-n* in polprevodniške naprave

3. Tranzistor:



1907

1947

1963

The Nobel Prize in Physics 1956

William Bradford Shockley
Prize share: 1/3

John Bardeen
Prize share: 1/3

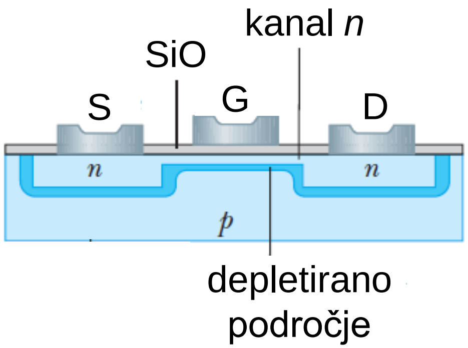
Walter Houser Brattain
Prize share: 1/3

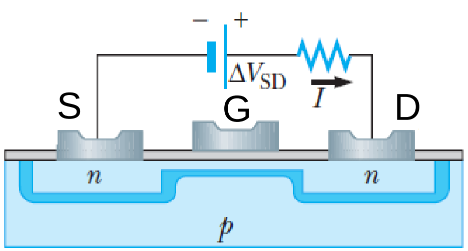
The Nobel Prize in Physics 1956 was awarded jointly to William Bradford Shockley, John Bardeen and Walter Houser Brattain *"for their researches on semiconductors and their discovery of the transistor effect"*.

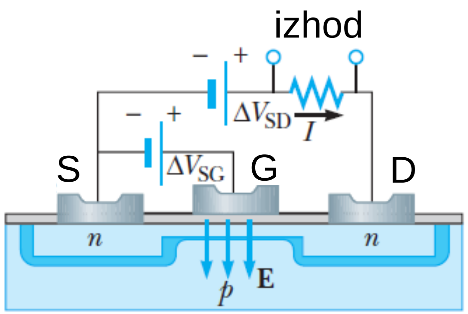
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

9.7 Stik *p-n* in polprevodniške naprave

4. FET:



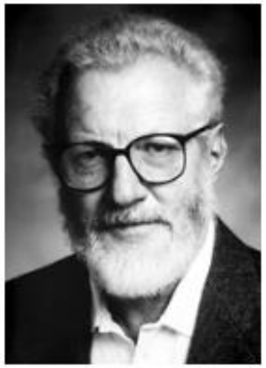




5. Tiskano vezje:

The Nobel Prize in Physics 2000

Zhores I. Alferov
Prize share: 1/4



Herbert Kroemer
Prize share: 1/4

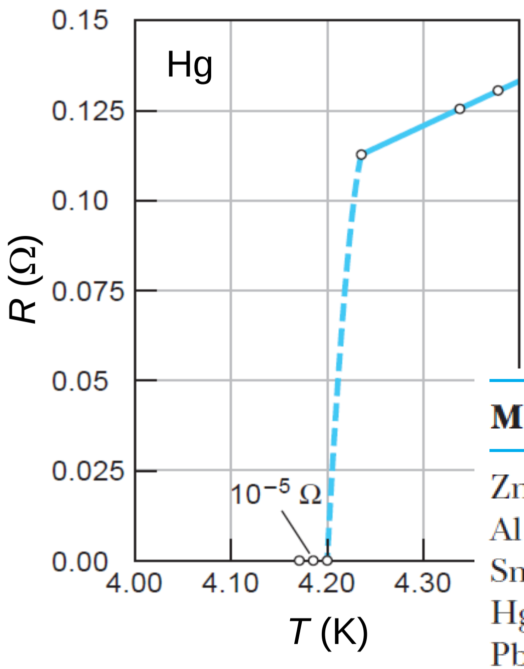
Jack S. Kilby
Prize share: 1/2

The Nobel Prize in Physics 2000 was awarded *"for basic work on information and communication technology"* with one half jointly to Zhores I. Alferov and Herbert Kroemer *"for developing semiconductor heterostructures used in high-speed- and opto-electronics"* and the other half to Jack S. Kilby *"for his part in the invention of the integrated circuit"*.

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

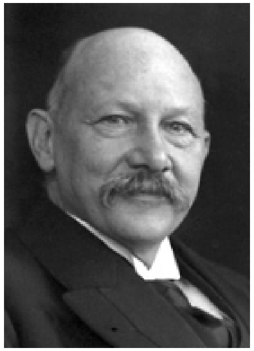
9.8 Superprevodnost

- Ohmov zakon: $U = IR$



Material	T_c(K)
Zn	0.88
Al	1.19
Sn	3.72
Hg	4.15
Pb	7.18
Nb	9.46
Nb_3Sn	18.05
Nb_3Ge	23.2
$YBa_2Cu_3O_7$	92
Bi–Sr–Ca–Cu–O	105
Tl–Ba–Ca–Cu–O	125
$HgBa_2Ca_2Cu_3O_8$	134

The Nobel Prize in Physics 1913



Heike Kamerlingh Onnes
Prize share: 1/1

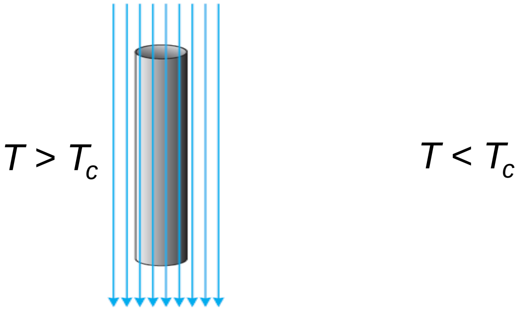
The Nobel Prize in Physics 1913 was awarded to Heike Kamerlingh Onnes *"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"*.

SIMULACIJA

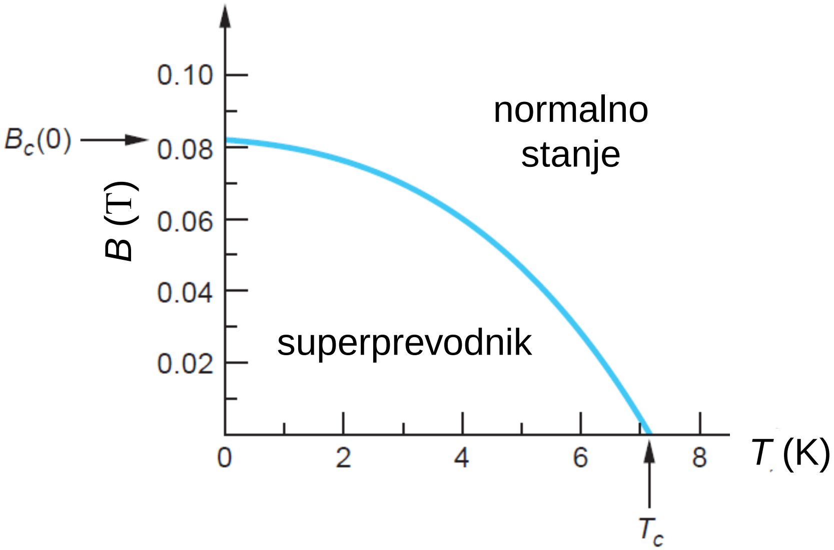
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

9.8 Superprevodnost

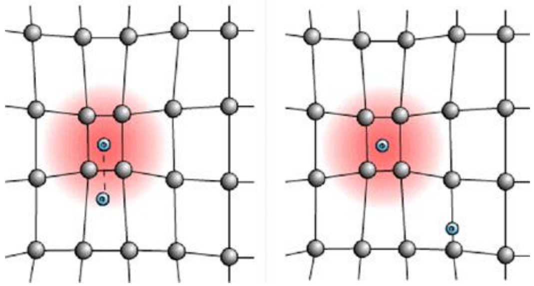
- Meissnerjev efekt: levitacija



- Kritično polje:



- Teorija BCS: Cooperjevi pari



The Nobel Prize in Physics 1972

John Bardeen
Prize share: 1/3

Leon Neil Cooper
Prize share: 1/3

John Robert Schrieffer
Prize share: 1/3

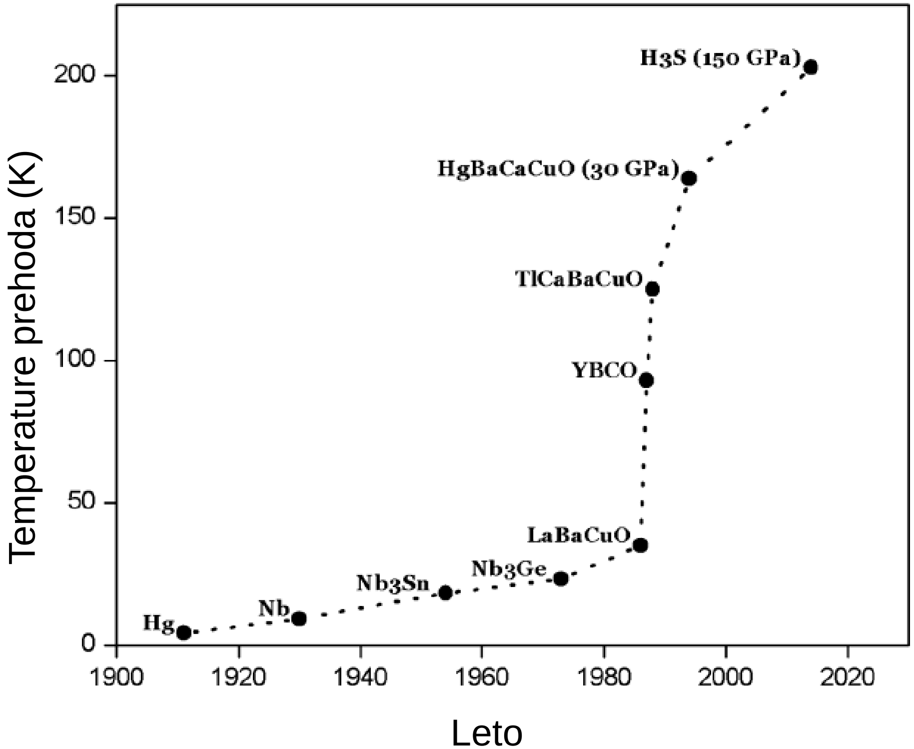
The Nobel Prize in Physics 1972 was awarded jointly to John Bardeen, Leon Neil Cooper and John Robert Schrieffer *"for their jointly developed theory of superconductivity, usually called the BCS-theory".*

SIMULACIJA

Vir: internet; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

9.8 Superprevodnost

- Visokotemperaturna superprevodnost: keramika



The Nobel Prize in Physics 1987

J. Georg Bednorz
Prize share: 1/2

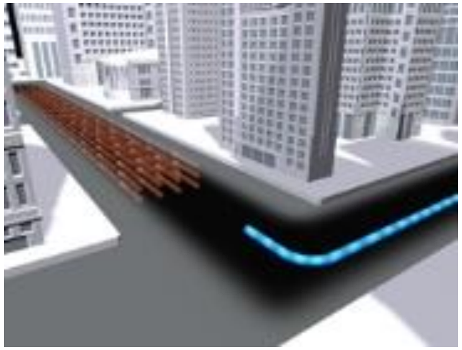
K. Alexander Müller
Prize share: 1/2

The Nobel Prize in Physics 1987 was awarded jointly to J. Georg Bednorz and K. Alexander Müller *"for their important break-through in the discovery of superconductivity in ceramic materials"*

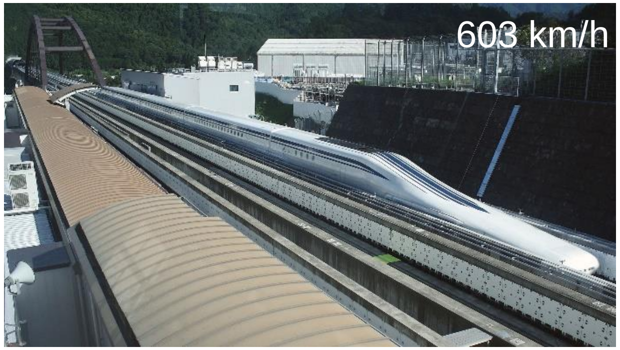
Vir: internet

9.8 Superprevodnost

- Uporabnost:



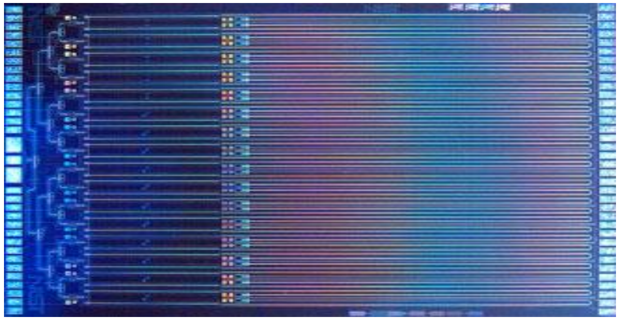
PRENOS EL. ENERGIJE



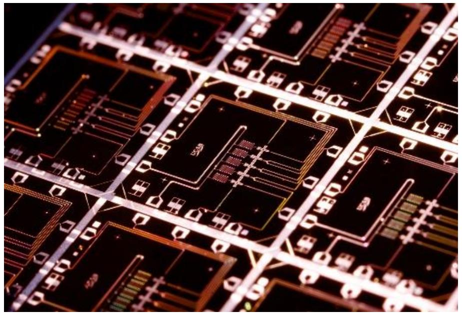
PREMIKANJE BREZ TRENJA

SUPERPREVODNI MAGNETI

SQUID MAGNETOMETER



OBČUTLJIVI DETEKTORJI DELCEV



KVANTNO RAČUNALNIŠTVO

Vir: internet

Univerza *v Ljubljani*
Fakulteta za *matematiko in fiziko*

MODERNA FIZIKA

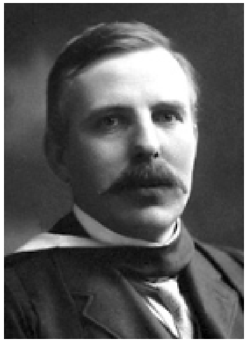
Jedrska fizika

Andrej Zorko
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

10.1 Lastnosti jeder

- Prelomnice v jedrski fiziki:
  - l. 1896: odkritje radioaktivnosti - rojstvo jedrske fizike (Becquerel)
  - l. 1898: izolacija radija (zakonca Curie)
  - l. 1911: odkritje jedra (Rutherford)

The Nobel Prize in Chemistry 1908

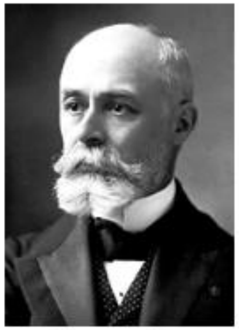


Ernest Rutherford
Prize share: 1/1

The Nobel Prize in Chemistry 1908 was awarded to Ernest Rutherford *"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"*.

Vir: internet

The Nobel Prize in Physics 1903



Antoine Henri Becquerel
Prize share: 1/2

Pierre Curie
Prize share: 1/4

Marie Curie, née Sklodowska
Prize share: 1/4

The Nobel Prize in Physics 1903 was divided, one half awarded to Antoine Henri Becquerel *"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"*, the other half jointly to Pierre Curie and Marie Curie, née Sklodowska *"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"*.

10.1 Lastnosti jeder

- Prelomnice v jedrski fiziki:
  - l. 1930: odkritje jedrskih reakcij (Cockcroft & Walton)
  - l. 1932: odkritje nevtrona (Chaldwick)

The Nobel Prize in Physics 1951

Sir John Douglas Cockcroft
Prize share: 1/2

Ernest Thomas Sinton Walton
Prize share: 1/2

The Nobel Prize in Physics 1951 was awarded jointly to Sir John Douglas Cockcroft and Ernest Thomas Sinton Walton *"for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles"*

The Nobel Prize in Physics 1935

James Chadwick
Prize share: 1/1

The Nobel Prize in Physics 1935 was awarded to James Chadwick *"for the discovery of the neutron".*

Vir: internet

10.1 Lastnosti jeder

- Prelomnice v jedrski fiziki:
  - l. 1933: odkritje umetne radioaktivnosti (Irène & Frédéric Joliot-Curie)
  - l. 1938: odkritje jedrske fisije (Meitner, Hahn, Strassmann)
  - l. 1942: razvoj prvega jedrskega reaktorja (Fermi)

The Nobel Prize in Physics 1938

Enrico Fermi
Prize share: 1/1

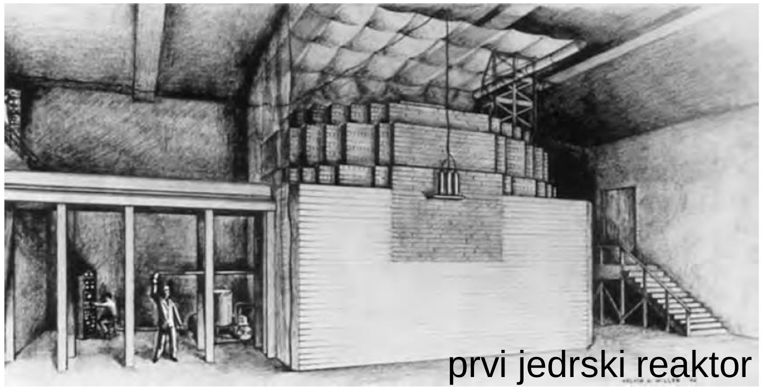
The Nobel Prize in Physics 1938 was awarded to Enrico Fermi *"for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"*.

The Nobel Prize in Chemistry 1935

Frédéric Joliot
Prize share: 1/2

Irène Joliot-Curie
Prize share: 1/2

The Nobel Prize in Chemistry 1935 was awarded jointly to Frédéric Joliot and Irène Joliot-Curie *"in recognition of their synthesis of new radioactive elements"*



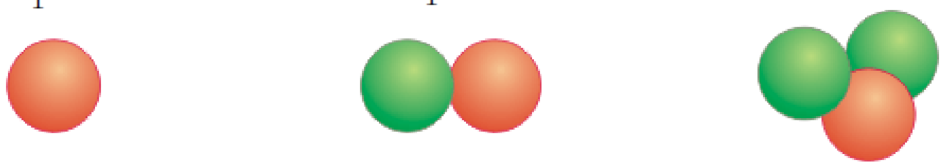
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

10.1 Lastnosti jeder

- Sestava jeder (nukleoni): $^{A}_{Z}X$
  - vrstno (atomsko) število (protoni): *Z*
  - nevtronsko število (nevtroni): *N*
  - masno število (nukleoni): *A* = *Z* + *N*

Izotopi:

$^{1}_{1}H$ $^{2}_{1}H$ $^{3}_{1}H$



vodik (99.98%) — devterij (0.02%) — tritij

- Naboj jeder: Ze_0

- Masa:

$$M(^{A}_{Z}X) \neq Zm_p + (A-Z)m_n + Zm_e$$

$$1u \equiv \frac{1}{12}\frac{M(^{12}C)}{N_A} = 1{,}66 \times 10^{-27}\,\mathrm{kg}$$

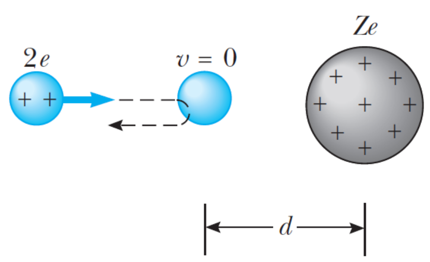
$$= 931{,}49\,\mathrm{MeV/c^2}$$

	masa		
delec	**kg**	**u**	**MeV/c²**
proton	$1.672\,623 \times 10^{-27}$	1.007 276	938.272 3
nevtron	$1.674\,929 \times 10^{-27}$	1.008 665	939.565 6
elektron	$9.109\,390 \times 10^{-31}$	$5.48\,579\,9 \times 10^{-4}$	0.510 999 1

- Velikost jeder: Rutherfordovo sipanje

$$r = r_0 A^{1/3}$$ (kapljična narava)

$$r_0 = 1{,}2\ \mathrm{fm}$$



Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

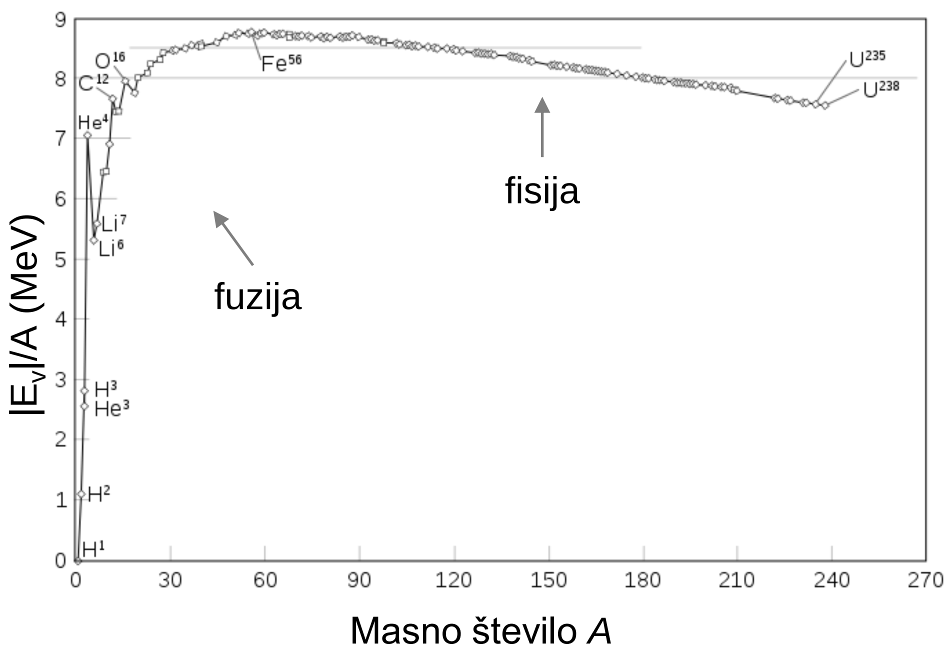
10.1 Lastnosti jeder

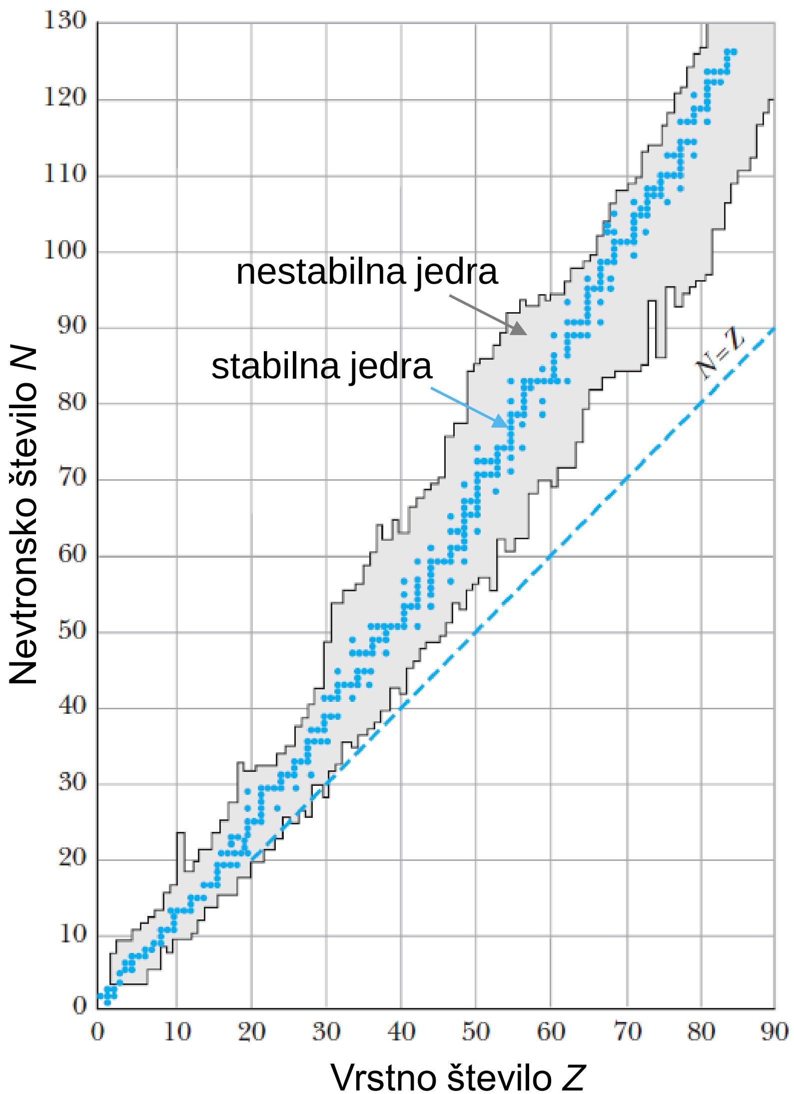
- Stabilnost jeder:

  magična števila: 2, 8, 20, 28, 50, 82, 126
  (lupinska struktura)

- Vezavna energija:

$$E_v = \left[m({}^A_Z X) - Z m({}^1_1 H) - (A-Z) m_n\right] c^2$$





Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

10.1 Lastnosti jeder

➢ Jedrska sila in potencial:

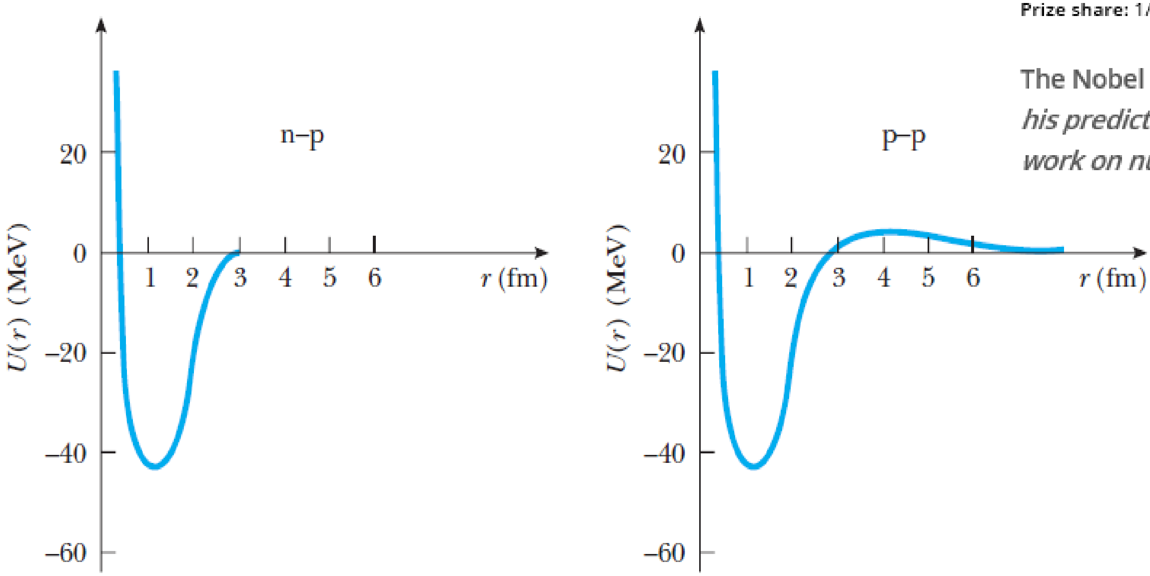
- kratek doseg (nekaj fm)
- sila neodvisna od naboja nukleona

The Nobel Prize in Physics 1949

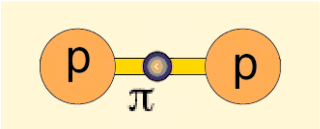
Hideki Yukawa

Prize share: 1/1

The Nobel Prize in Physics 1949 was awarded to Hideki Yukawa *"for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces".*



model izmenjave delcev (mezonov)



Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

1. Kapljični model (Weiszäcker, l. 1935):

➢ Semiempirična masna formula:

$$E_v = -w_0 A + w_1 A^{2/3} + w_2 \frac{Z^2}{A^{1/3}} + w_3 \frac{(A-2Z)^2}{A} + w_4 \frac{\delta_{ZN}}{A^{3/4}}$$

volumski efekt	površinski efekt	Coulombski odboj	mešalni efekt	efekt parjenja

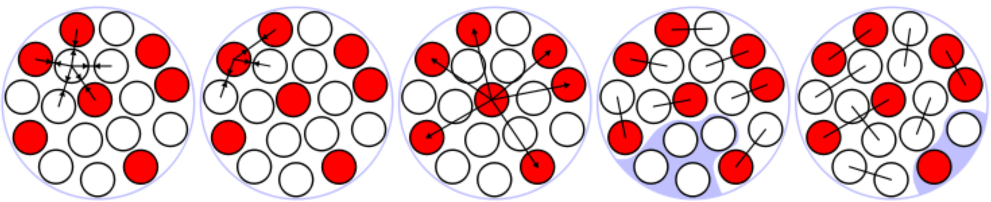
$w_0 = 15{,}7\ \mathrm{MeV}$

$w_1 = 17{,}8\ \mathrm{MeV}$

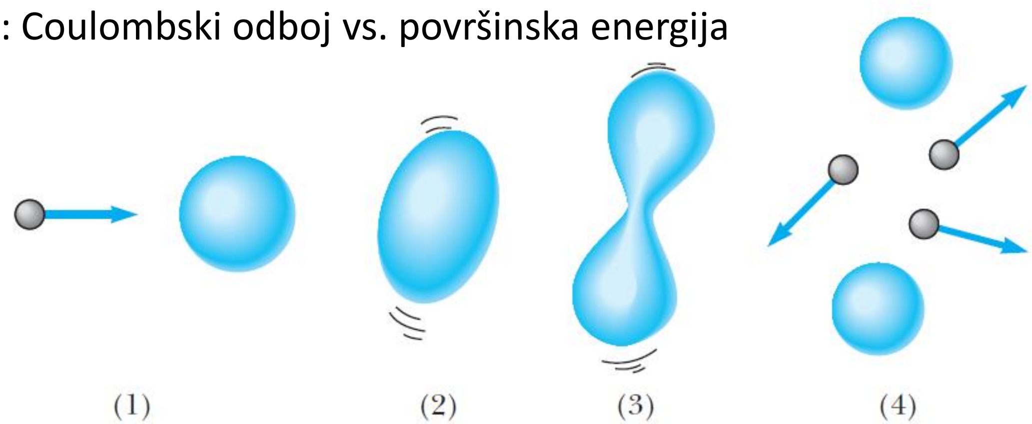
$w_2 = 0{,}71\ \mathrm{MeV}$

$w_3 = 23{,}6\ \mathrm{MeV}$

$w_4 = 33{,}5\ \mathrm{MeV}$



➢ Jedrski razpad: Coulombski odboj vs. površinska energija

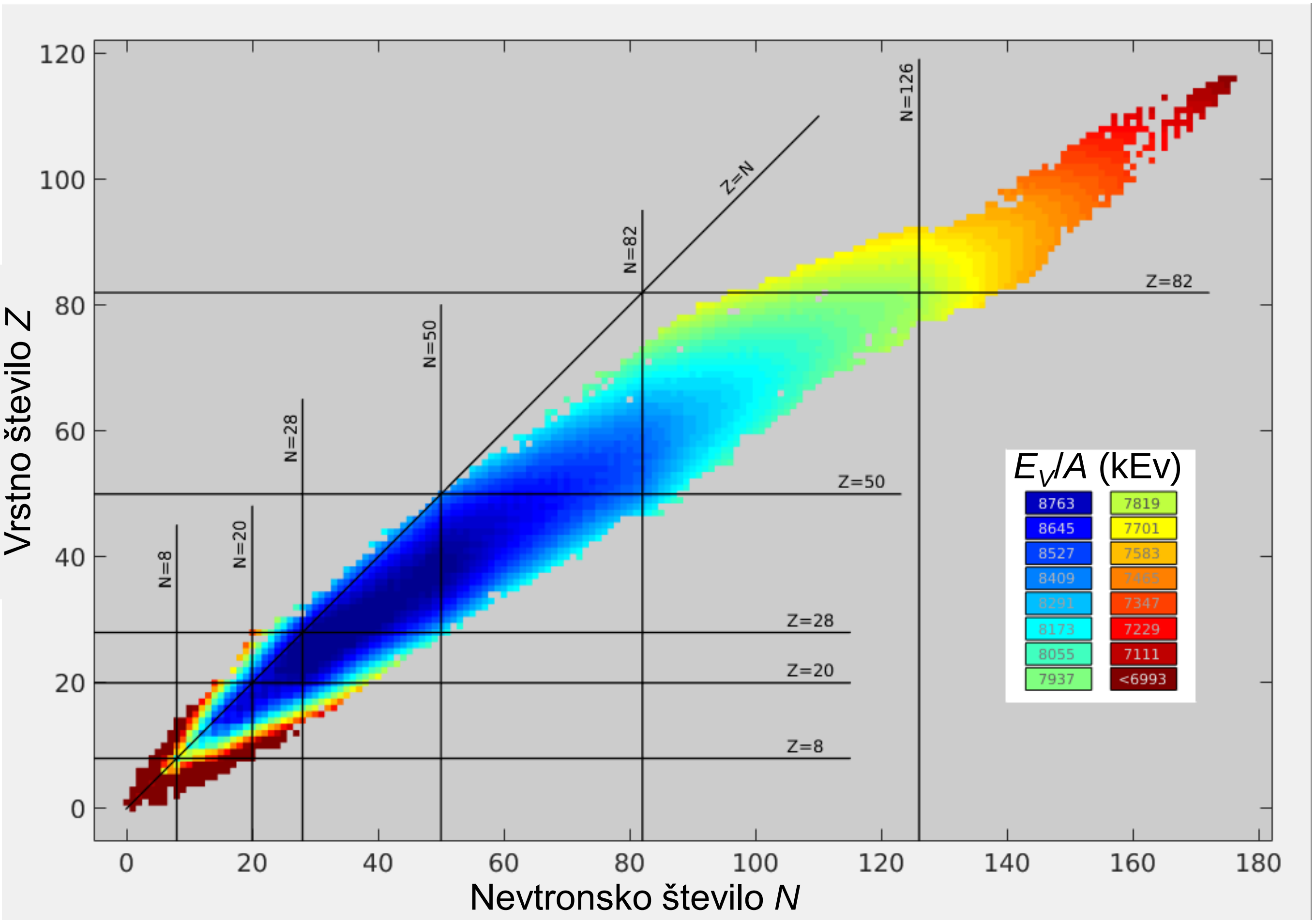


Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

10.2 Fizikalni modeli jedra

- Dolina stabilnosti:

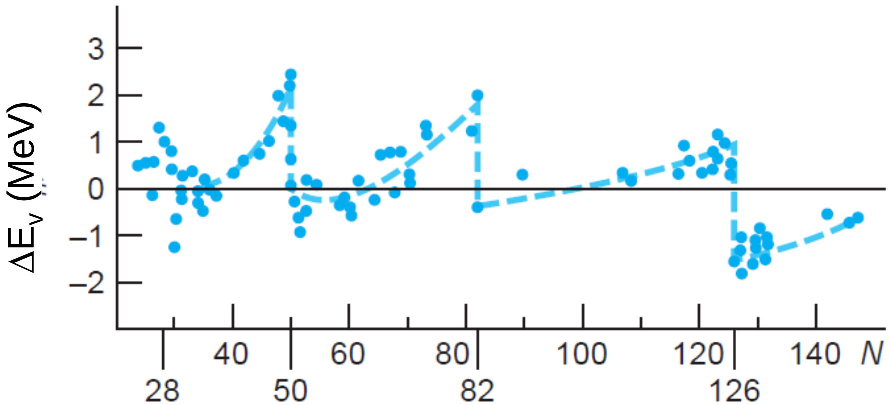
$$\frac{N}{Z} \approx 1 + \frac{w_2}{2w_3} A^{2/3}$$



Vir: internet

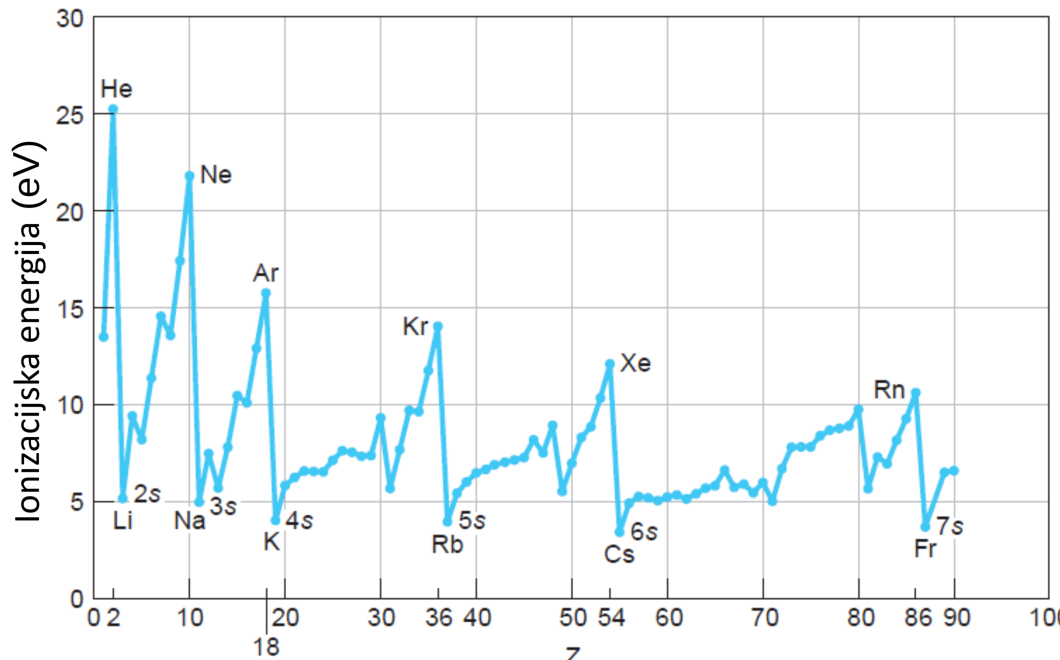
10.2 Fizikalni modeli jedra

2. Lupinski model (Goeppert-Mayer, Jensen):



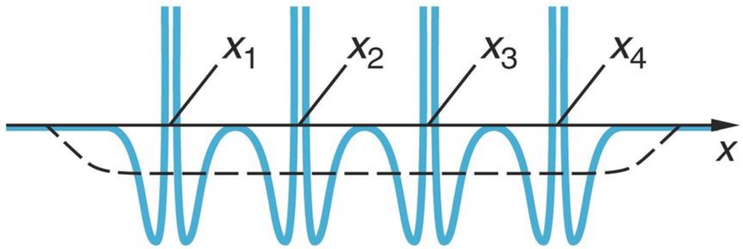
- Magična števila: 2, 8, 20, 28, 50, 82, 126

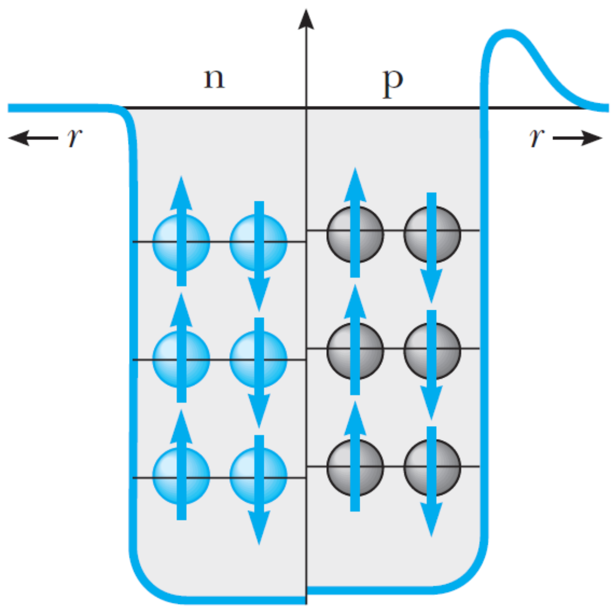
- Analogija z lupinskim modelom elektronov v atomu:



Vir: povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

- Neodvisni delci: Paulijevo izključitveno načelo





The Nobel Prize in Physics 1963

Eugene Paul Wigner
Prize share: 1/2

Maria Goeppert Mayer
Prize share: 1/4

J. Hans D. Jensen
Prize share: 1/4

The Nobel Prize in Physics 1963 was divided, one half awarded to Eugene Paul Wigner *"for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles"*, the other half jointly to Maria Goeppert Mayer and J. Hans D. Jensen *"for their discoveries concerning nuclear shell structure"*.

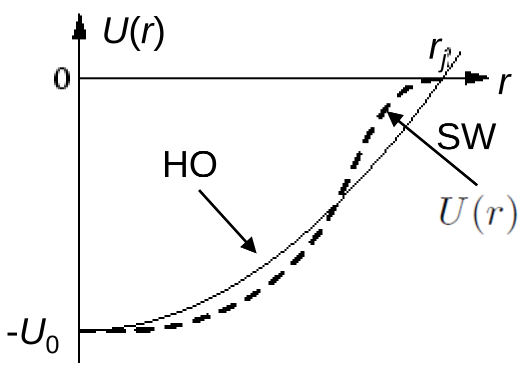
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005; Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

- Potencial: 3D harmonski oscilator (HO)

$$E = \hbar\omega\left(n_x + n_y + n_z + \frac{3}{2}\right) = \hbar\omega\left(n + \frac{1}{2}\right) \qquad n = 2n_r + l + 1$$

degeneracija: $n(n+1)$

- Potencial: Saxon-Woods (SW)

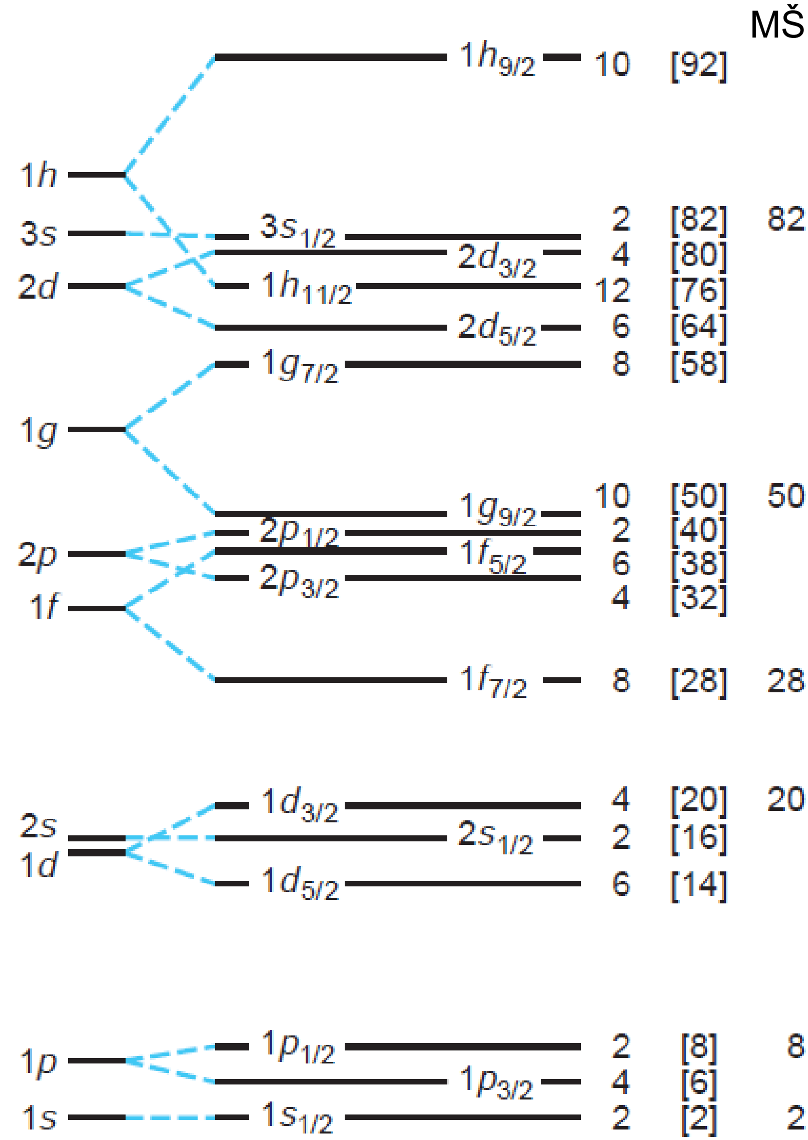


$$U(r) = -\frac{U_0}{e^{(r-r_j')/s} + 1}$$

- Sklopitev *ls*: $E_{ls} = -\eta\,\vec{l}\cdot\vec{s}$

$$E(I = l + \frac{1}{2}) < E(I = l - \frac{1}{2})$$

degeneracija: $2I + 1$



Vir: internet; povzeto po Tipler & Llevellyn, Modern Physics, W. H. Freeman and Company, 2012

10.3 Jedrski magnetizem

- Magnetni moment jedra: $\vec{\mu} = \frac{g\mu_j}{\hbar}\vec{J} = \gamma\vec{J}$ $\quad \vec{J} = \hbar\vec{I}$

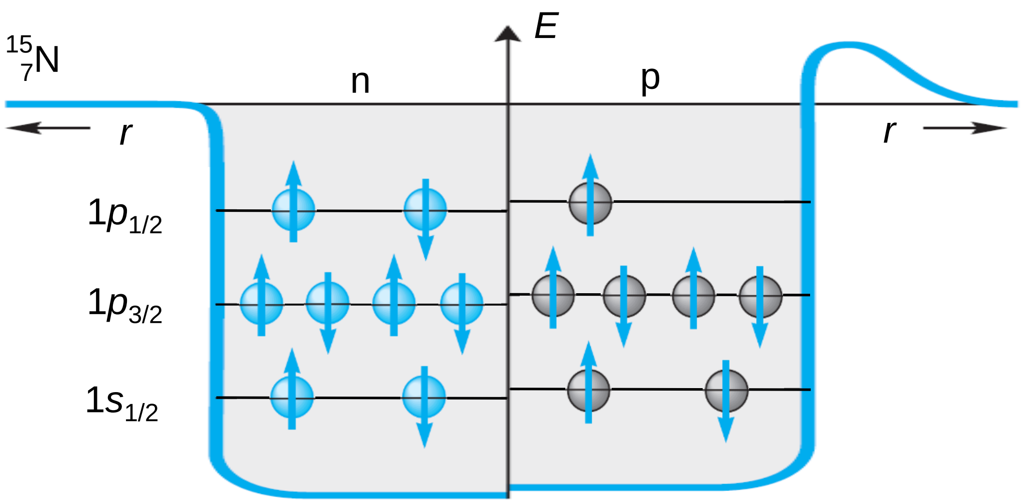
  $\mu_z = \gamma J_z$

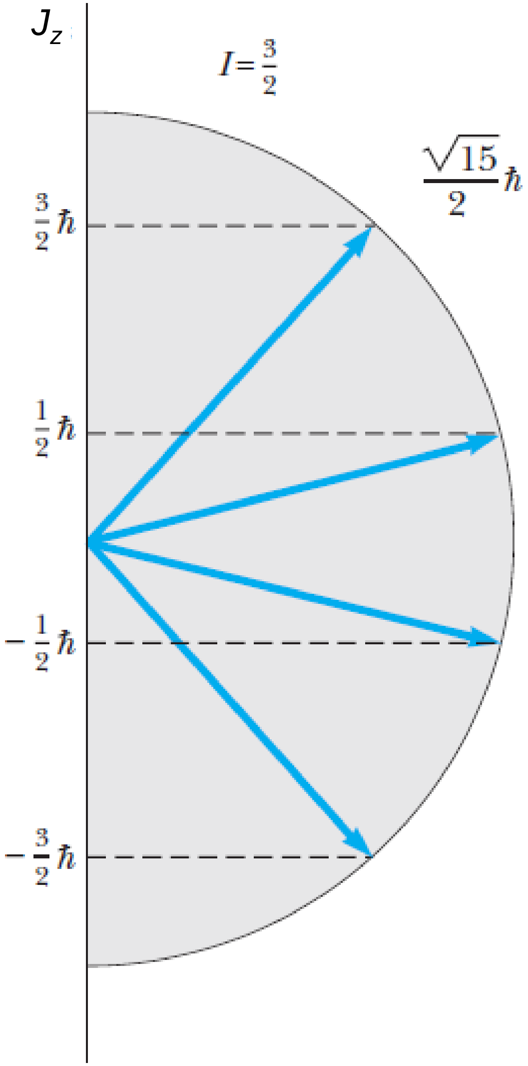
- Jedrski magneton: $\mu_j = \frac{e_0\hbar}{2m_p} = 5{,}05 \times 10^{-27}\ \mathrm{Am}^2$

- Giromagnetno razmerje: γ

- Kvantizacija momenta: $\mu_z = \gamma\hbar m$

- Spin jedra (lupinski model):





Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

10.3 Jedrski magnetizem

- Jedrska magnetna resonanca (NMR):

$$\Delta E = \gamma \hbar B_0 = h\nu_L$$

The Nobel Prize in Physics 1952

Felix Bloch
Prize share: 1/2

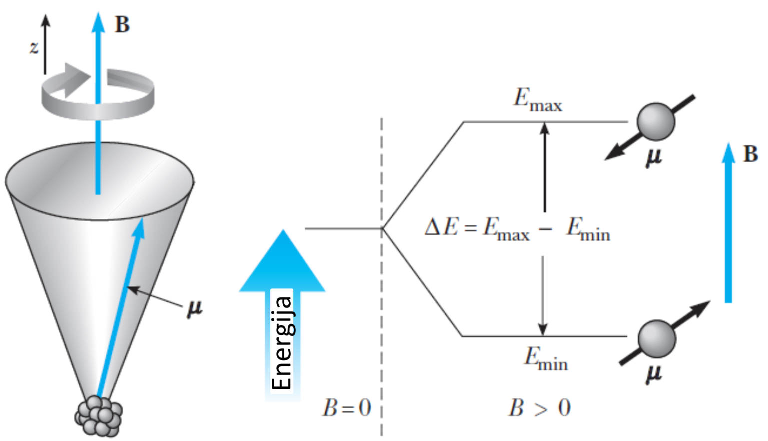
Edward Mills Purcell
Prize share: 1/2

The Nobel Prize in Physics 1952 was awarded jointly to Felix Bloch and Edward Mills Purcell *"for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith"*

The Nobel Prize in Physics 1944

Isidor Isaac Rabi
Prize share: 1/1

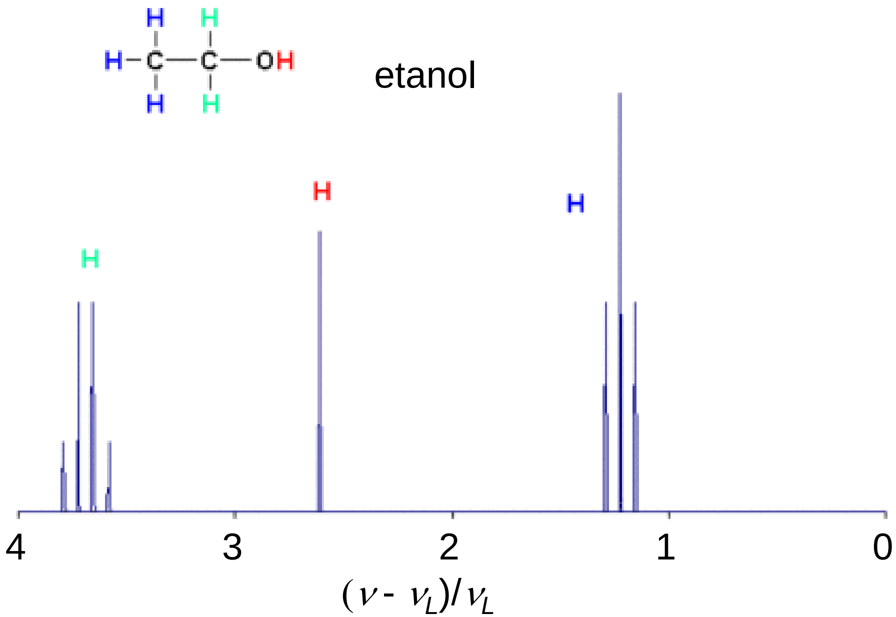
The Nobel Prize in Physics 1944 was awarded to Isidor Isaac Rabi *"for his resonance method for recording the magnetic properties of atomic nuclei"*.

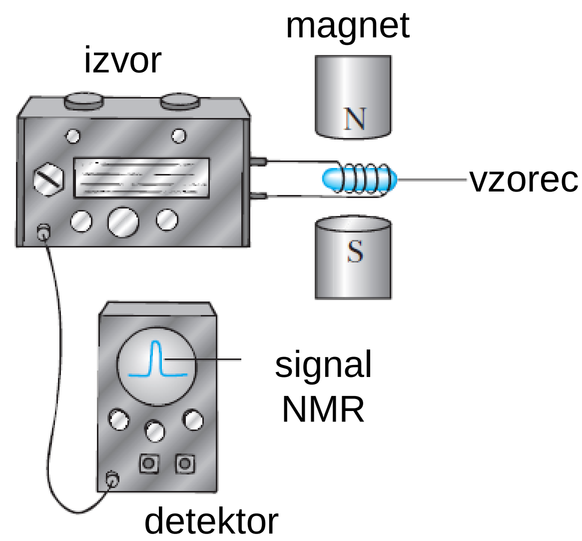


Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

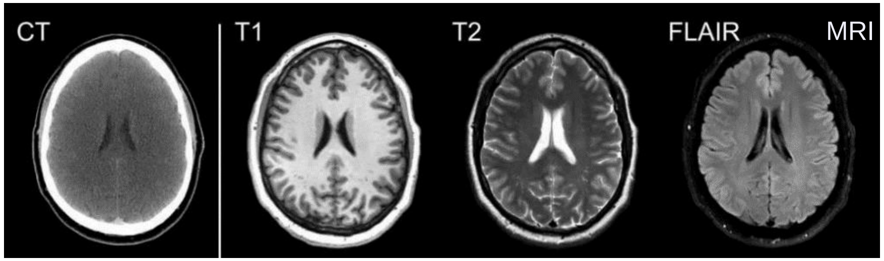
10.3 Jedrski magnetizem

- Jedrska magnetna resonanca (NMR): eksperiment





- Slikanje (MRI):

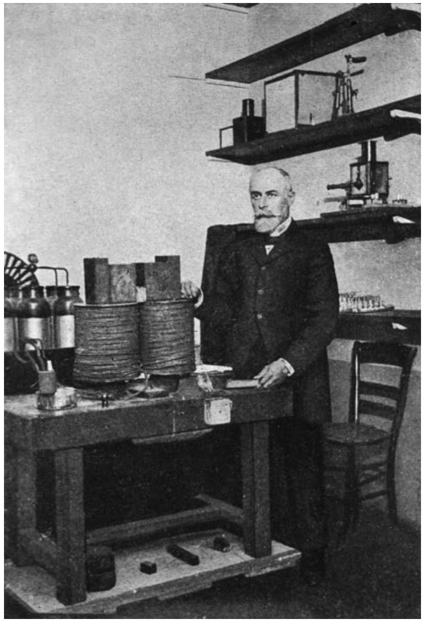


SIMULACIJA

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

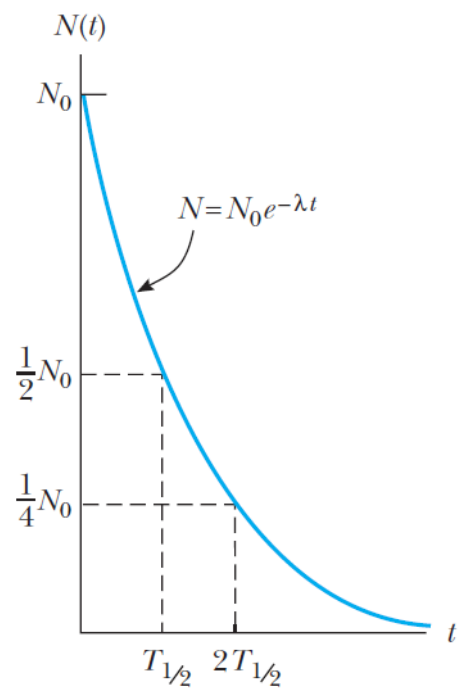
- Antoine Henri Becquerel (l. 1896): $K_2(UO_2)(SO4)_2$

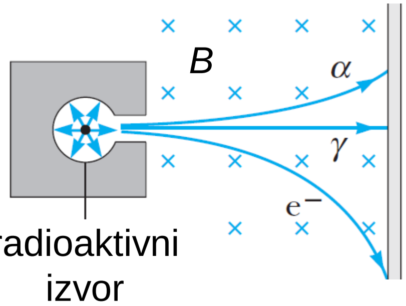
  I will insist particularly upon the following fact, which seems to me quite important and beyond the phenomena which one could expect to observe: The same crystalline crusts [of potassium uranyl sulfate], arranged the same way with respect to the photographic plates, in the same conditions and through the same screens, but sheltered from the excitation of incident rays and kept in darkness, still produce the same photographic images.



Antoine Henri Becquerel

- Tipi sevanja:
  - sevanje α
  - sevanje β
  - sevanje γ





- Razpadni zakon: $N(t) = N_0 \mathrm{e}^{-\lambda t} = N_0 \mathrm{e}^{-t/\tau}$

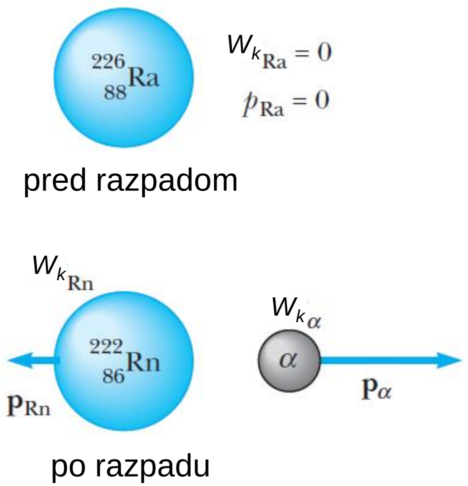
$$\tau = \frac{1}{\lambda} \qquad t_{1/2} = \ln 2 \cdot \tau$$

- Aktivnost: $A(t) = \left|\frac{\mathrm{d}N(t)}{\mathrm{d}t}\right| = \lambda N_0 \mathrm{e}^{-t/\tau}$

SIMULACIJA

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

1. Razpad α: $\quad {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\mathrm{He}$



- Energija: $Q = (m_X - m_Y - m_\alpha)c^2$

$$W_k^\alpha = \frac{m_Y}{m_Y + m_\alpha} Q$$

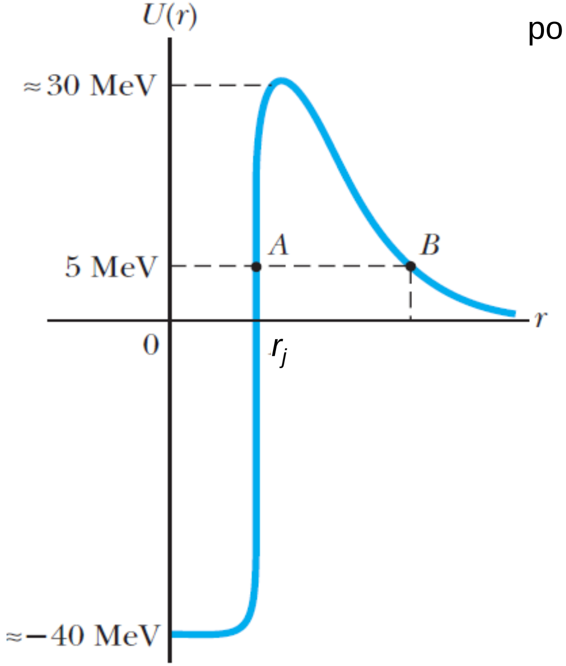
- Tuneliranje: Geiger-Nuttalova enačba

$$\ln\tau = \frac{a}{\sqrt{W_k^\alpha}} - b$$

$$a = \frac{e_0^2 (Z-2)\sqrt{2m_r}}{2\epsilon_0 \hbar}$$

$$b = \frac{4e_0}{\hbar}\sqrt{\frac{(Z-2)m_r r_j}{\pi\epsilon_0}} + \ln\left(\frac{W_k^\alpha}{2m_r r_j^2}\right)^{1/2}$$

$$m_r = \frac{m_Y m_\alpha}{m_Y + m_\alpha}$$

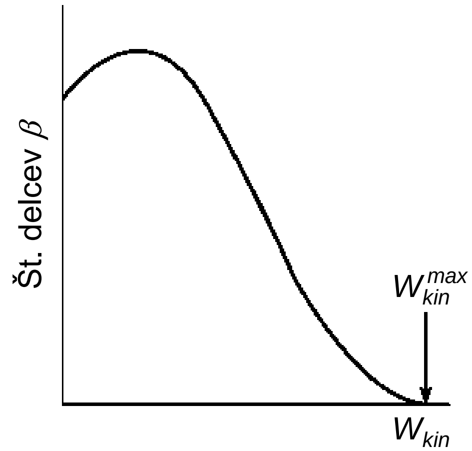


SIMULACIJA

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

10.4 Radioaktivnost in razpadni procesi

2. Razpad β:



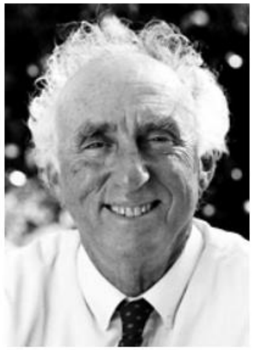
- Razpad β^-: $${}^{A}_{Z}X \rightarrow {}_{Z+1}^{\;\;A}Y + e^- + \bar{\nu}$$

$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + e^- + \bar{\nu} \quad (Q = 0.78\,\mathrm{MeV})$$

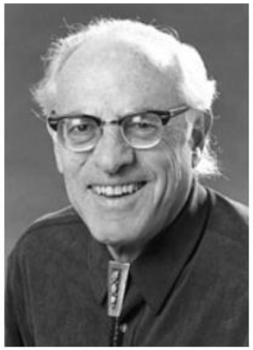
- Razpad β^+: $${}^{A}_{Z}X \rightarrow {}_{Z-1}^{\;\;A}Y + e^+ + \nu$$

- Ujetje elektrona: $${}^{A}_{Z}X + e^- \rightarrow {}_{Z-1}^{\;\;A}Y + \nu$$

The Nobel Prize in Physics 1995



Martin L. Perl
Prize share: 1/2



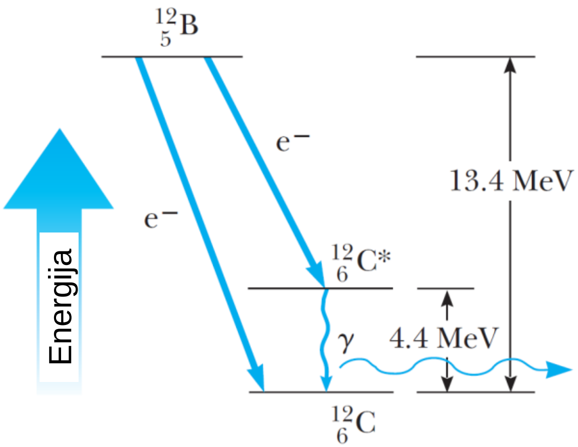
© University of California Regents
Frederick Reines
Prize share: 1/2

The Nobel Prize in Physics 1995 was awarded *"for pioneering experimental contributions to lepton physics"* jointly with one half to Martin L. Perl *"for the discovery of the tau lepton"* and with one half to Frederick Reines *"for the detection of the neutrino"*.

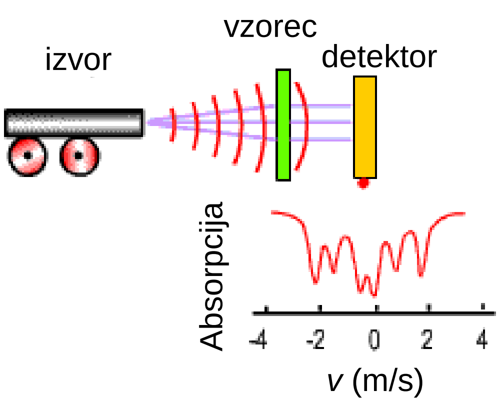
SIMULACIJA

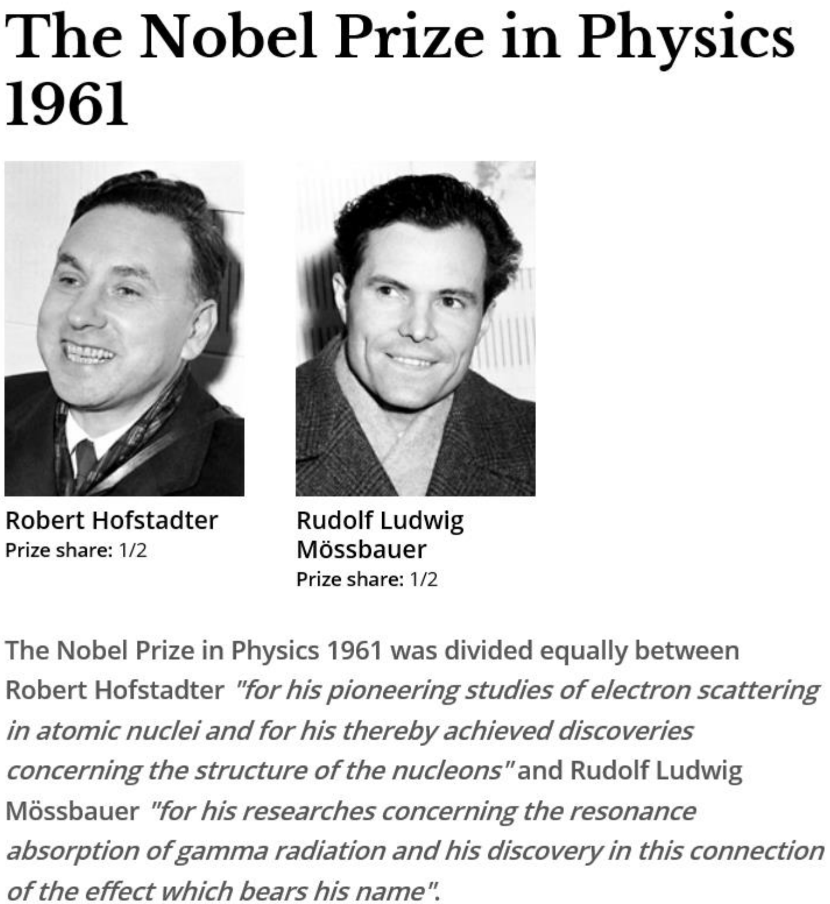
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

3. Razpad γ: ${}^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma$



- Mössbauerjeva spektroskopija: ^{57}Fe

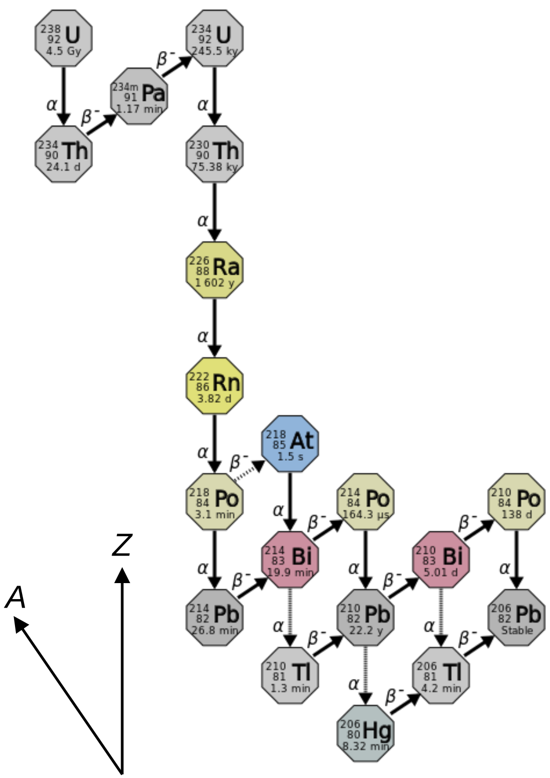




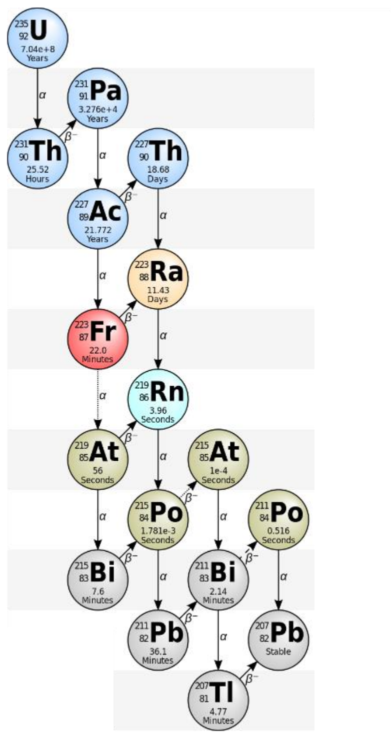
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

- Razpadni nizi:

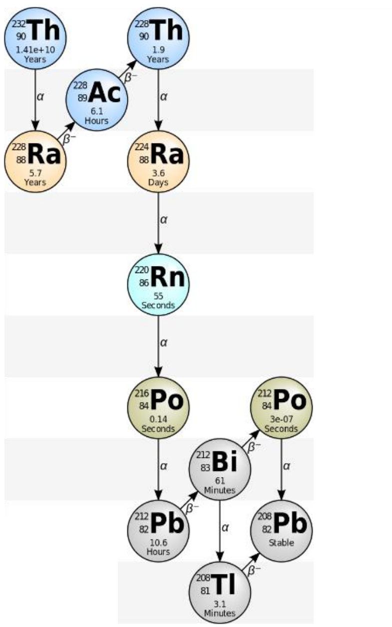
1. uranov niz:



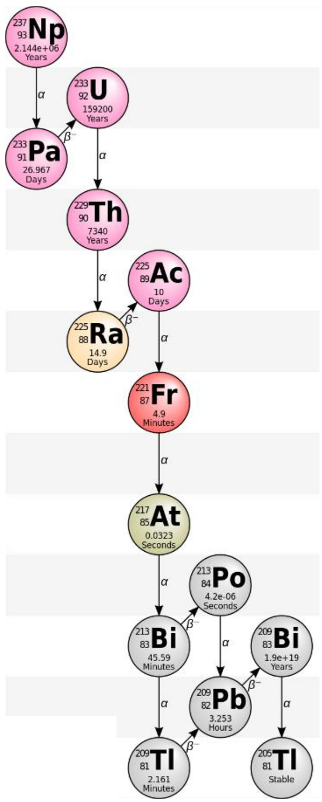
2. aktinijev niz:



3. torijev niz:



4. neptunijev niz:



Vir: internet

10.5 Jedrske reakcije

- Cockcroft, Walton (l. 1932):

$$ {}^{1}_{1}\mathrm{H} + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} $$

Walton Rutherford Cockcroft

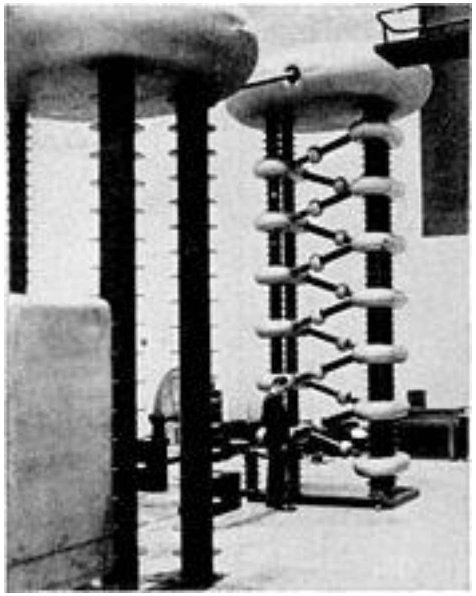
- Jedrska reakcija:

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

$$ X(a,b)Y $$

- Ohranitev:
  - masnega števila
  - naboja
  - energije, gibalne količine, vrtilne količine

$$ Q = W^{Y}_{kin} + W^{b}_{kin} - W^{X}_{kin} - W^{a}_{kin} $$
$$ = (m_X + m_a - m_Y - m_b)c^2 $$



1,2 MV generator Cockcrofta in Waltona

Vir: internet

10.5 Jedrske reakcije

- Število reakcij N_r:

$$\frac{N_r}{N_i} = \frac{\sigma N_j}{S}$$

- Tanka folija:

$$\mathrm{d}N_i = -\sigma n_j N_i \mathrm{d}x$$

$$j = j_0 \mathrm{e}^{-\sigma n_j x}$$

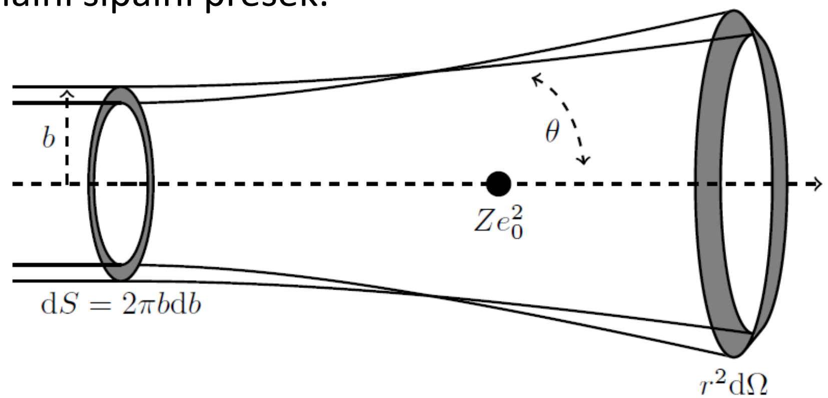
- Sipalni presek:

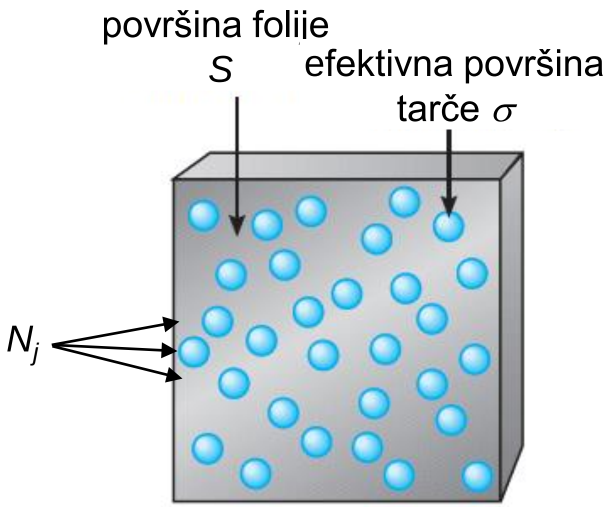
$$\bar{\nu} + p \rightarrow e^+ + n \quad (\sigma = 10^{-19}\,\mathrm{b})$$

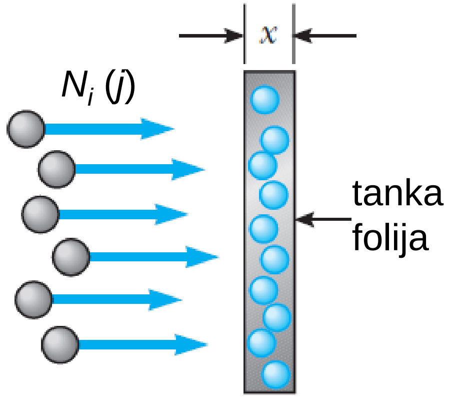
$$n + {}^{127}_{53}\mathrm{I} \rightarrow {}^{127}_{53}\mathrm{I}^* + n \quad (\sigma = 4\,\mathrm{b})$$

$$n + {}^{113}_{48}\mathrm{Cd} \rightarrow {}^{114}_{48}\mathrm{Cd} + \gamma \quad (\sigma = 10^4\,\mathrm{b})$$

- Diferencialni sipalni presek:





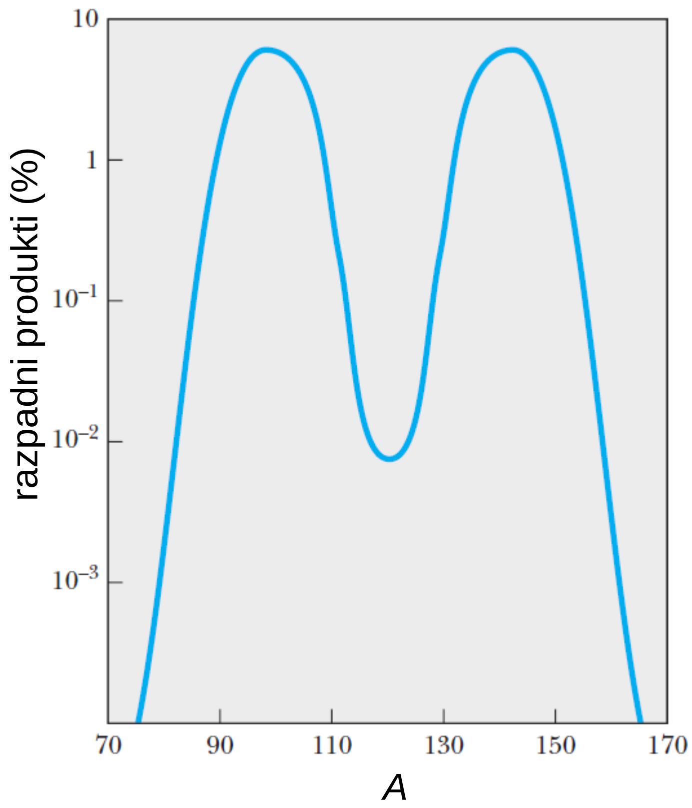


Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

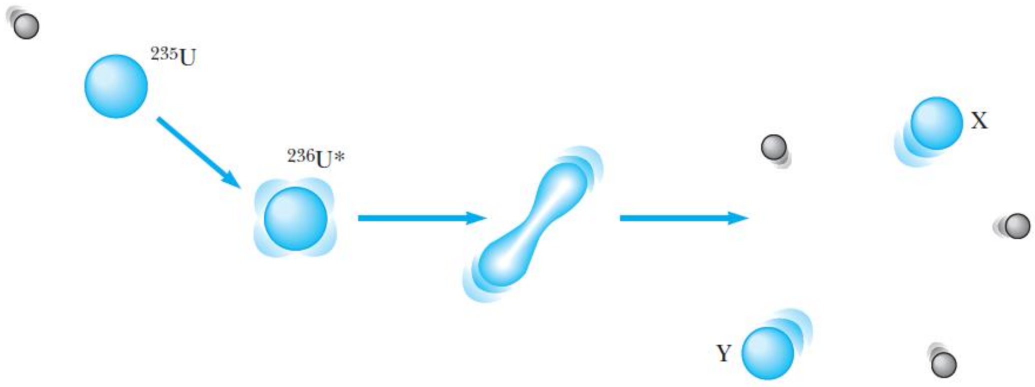
10.6 Razcep in zlivanje jeder

- Razcep jedra (fisija):

$$n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{141}_{92}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3n$$

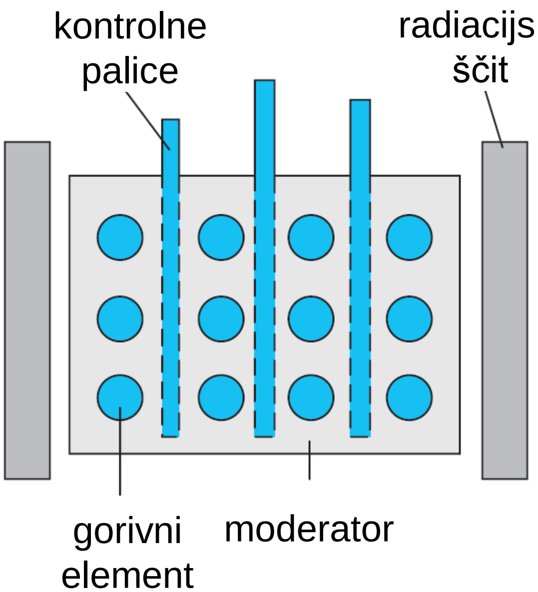


Strassmann Meitner Hahn

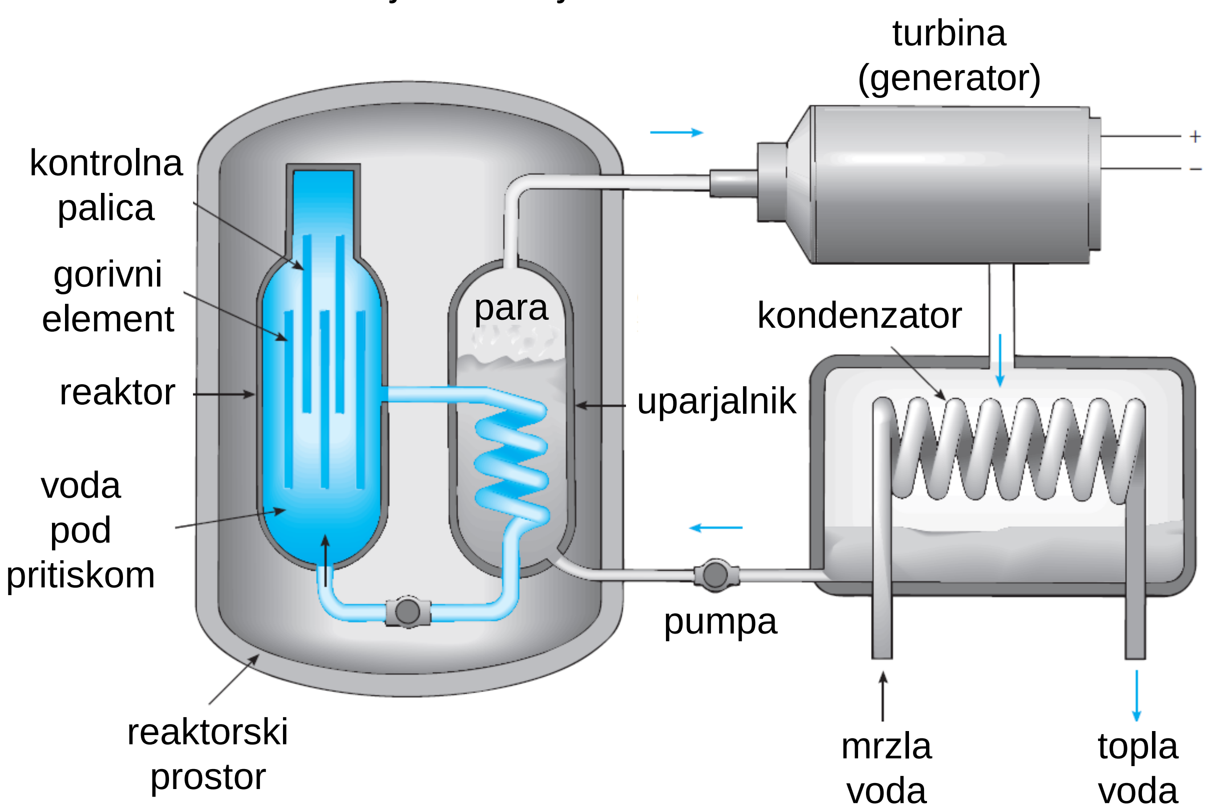


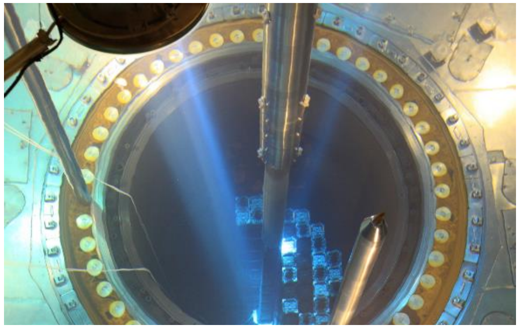
Vir: povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

- Komponente jedrskega reaktorja:



- Delovanje reaktorja:





Jedrski reaktor TRIGA (IJS)

SIMULACIJA

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

10.6 Razcep in zlivanje jeder

- Zlivanje jeder (fuzija): zvezde

vodikov cikel:

$$
\begin{aligned}
{}^1_1\mathrm{H} + {}^1_1\mathrm{H} &\rightarrow {}^2_1\mathrm{H} + e^+ + \nu_e \\
{}^1_1\mathrm{H} + {}^2_1\mathrm{H} &\rightarrow {}^3_2\mathrm{He} + \gamma \\
{}^3_2\mathrm{He} + {}^3_2\mathrm{He} &\rightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + {}^1_1\mathrm{H} \\
\sum : \quad 4\,{}^1_1\mathrm{H} &\rightarrow {}^4_2\mathrm{He} + 2e^+ + 2\nu_e + \gamma \\
(Q &= 26{,}3\,\mathrm{MeV})
\end{aligned}
$$

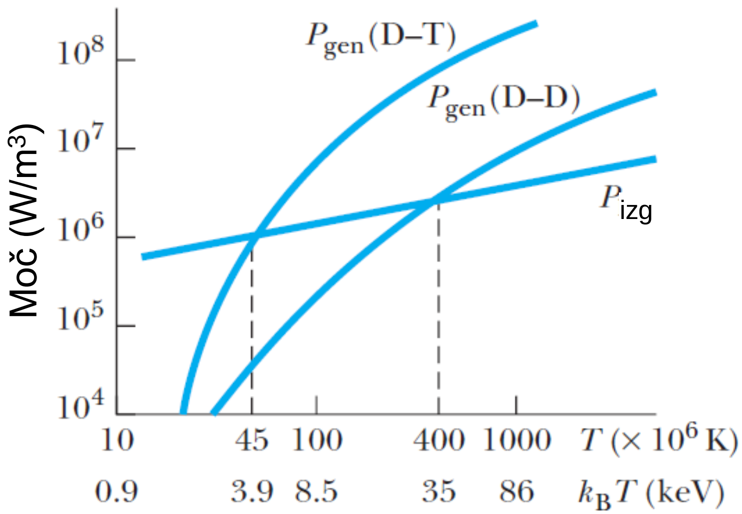
ogljiko-dušikov cikel:

$$
\begin{aligned}
{}^{12}_6\mathrm{C} + {}^1_1\mathrm{H} &\rightarrow {}^{13}_7\mathrm{N} + \gamma \\
{}^{13}_7\mathrm{N} &\rightarrow {}^{13}_6\mathrm{C} + e^+ + \nu_e \\
{}^{13}_6\mathrm{C} + {}^1_1\mathrm{H} &\rightarrow {}^{14}_7\mathrm{N} + \gamma \\
{}^{14}_7\mathrm{N} + {}^1_1\mathrm{H} &\rightarrow {}^{15}_8\mathrm{O} + \gamma \\
{}^{15}_8\mathrm{O} &\rightarrow {}^{15}_7\mathrm{N} + e^+ + \nu_e \\
{}^{15}_7\mathrm{N} + {}^1_1\mathrm{H} &\rightarrow {}^{12}_6\mathrm{C} + {}^4_2\mathrm{He} \\
\sum : \quad 4\,{}^1_1\mathrm{H} &\rightarrow {}^4_2\mathrm{He} + 2e^+ + 2\nu_e + 3\gamma \\
(Q &= 25{,}1\,\mathrm{MeV})
\end{aligned}
$$

Vir: internet

- Fuzijski reaktor:
- Kritični parametri:

  1. visoka kinetična energija (temperatura)

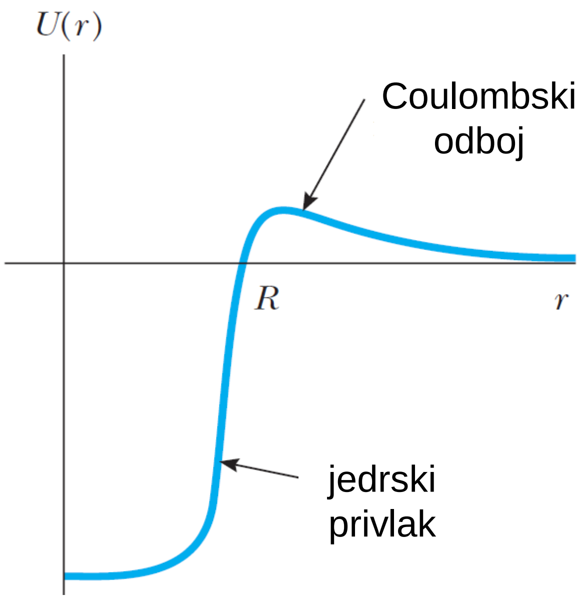


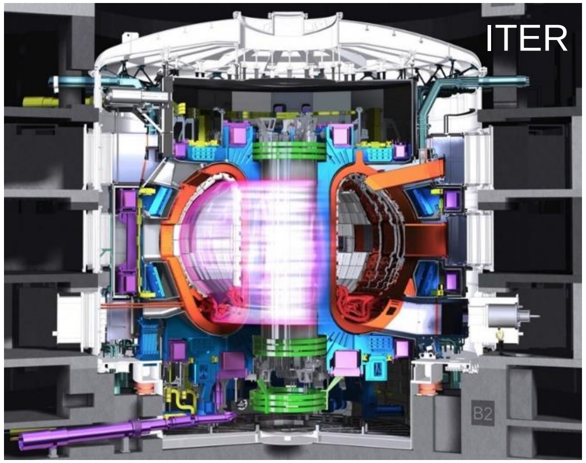
  2. velika gostota jeder *n*
  3. dolg čas zadrževanja plazme τ

Lawsonov kriterij:

$$n\tau \geq 10^{20}\ \mathrm{s/m^3} \quad (\mathrm{D-T})$$

$$n\tau \geq 10^{22}\ \mathrm{s/m^3} \quad (\mathrm{D-D})$$





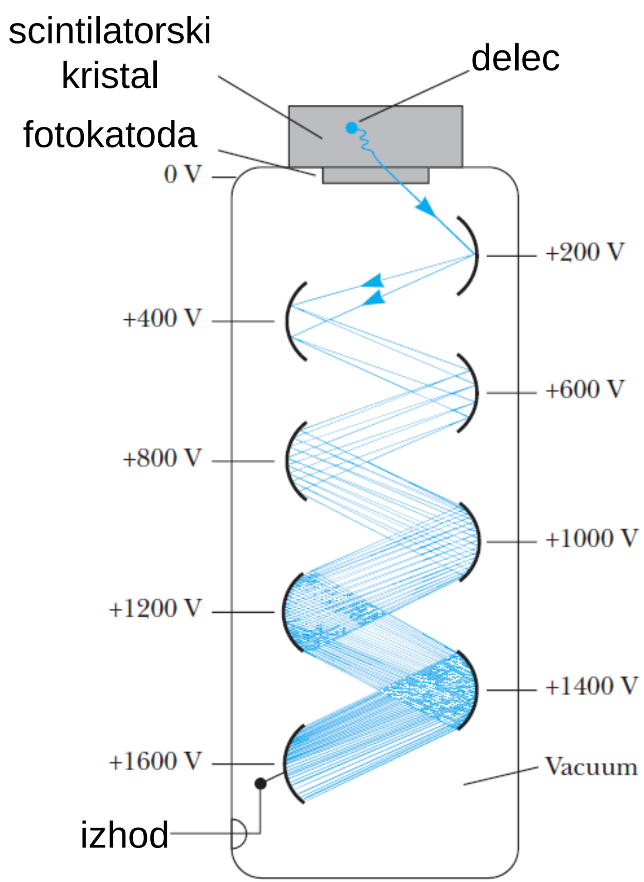
SIMULACIJA

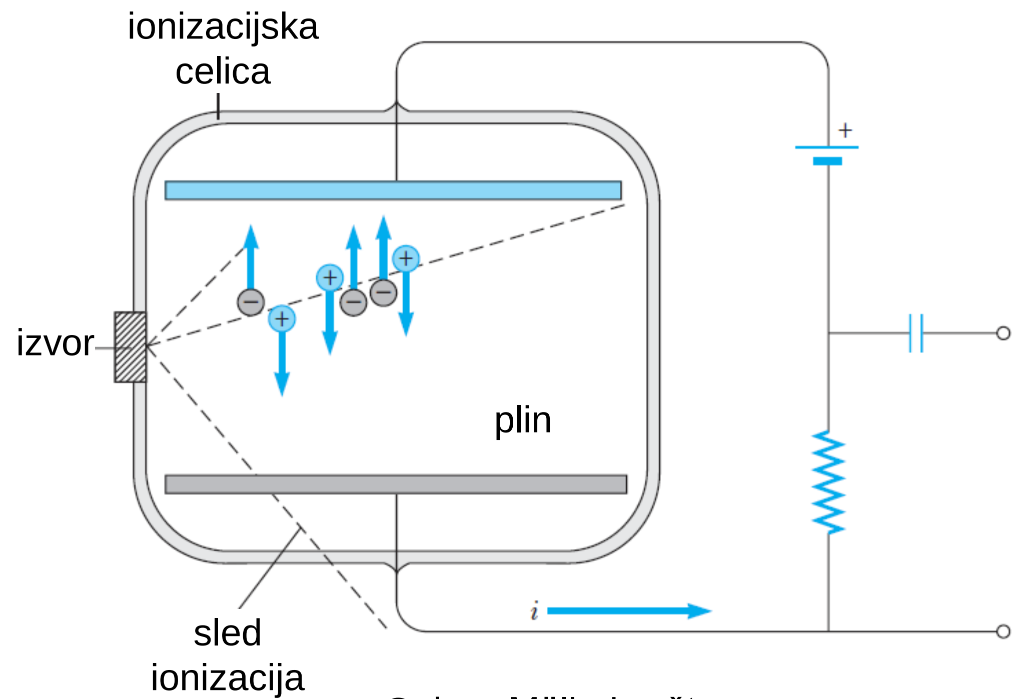
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

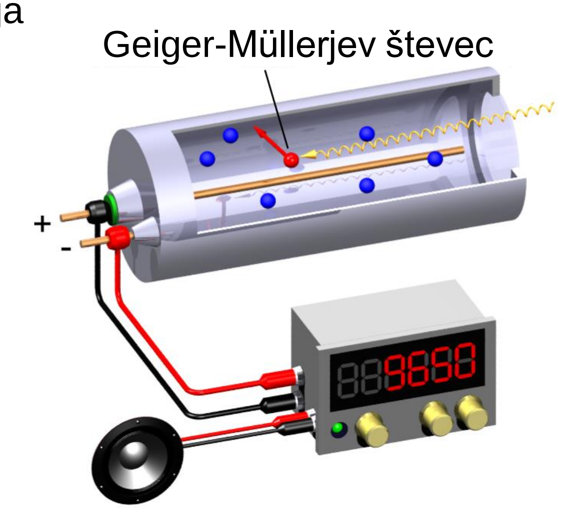
10.7 Posledice, meritve in uporaba radioakt. sevanja

➢ Merilniki sevanja:

1. ionizacijska celica
2. scintilacijski števec







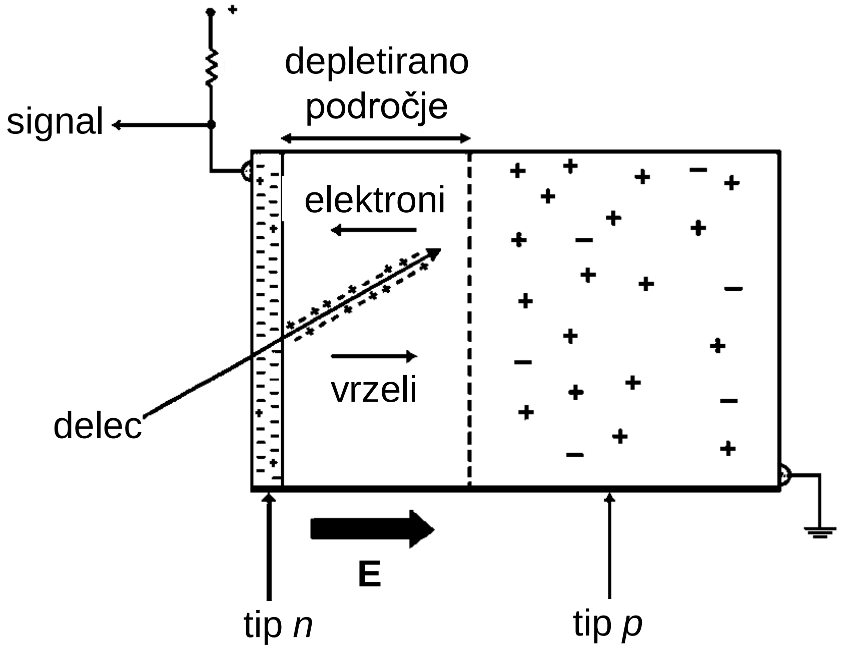
Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

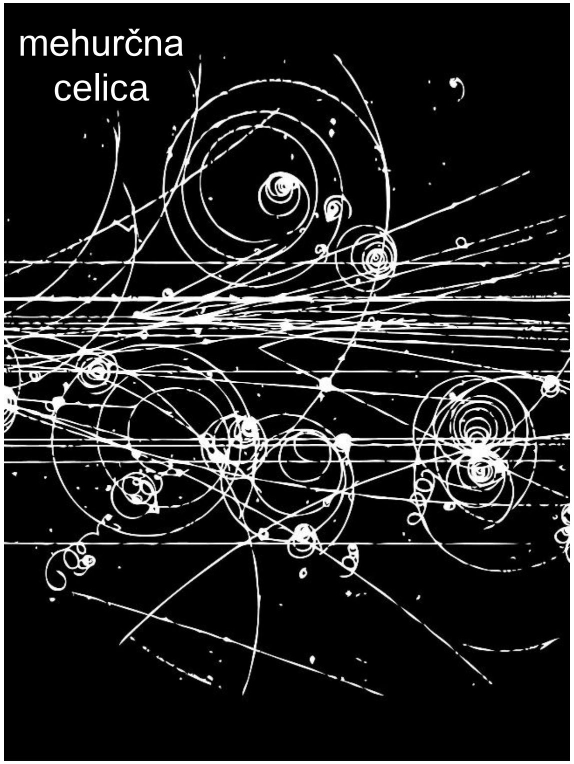
10.7 Posledice, meritve in uporaba radioakt. sevanja

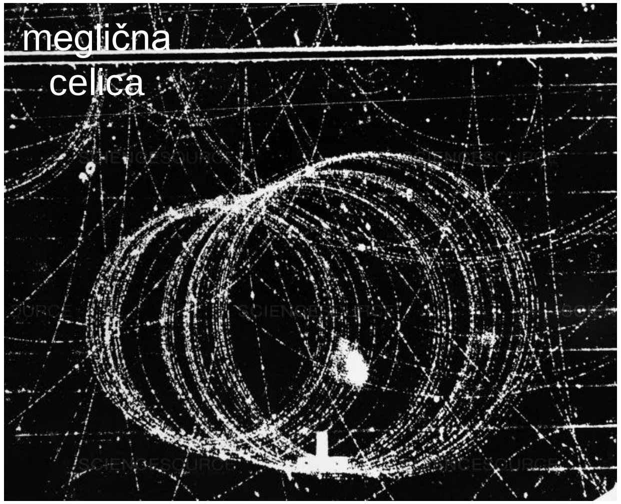
- Merilniki sevanja:

  3. polprevodniška dioda

  4. detektorji trajektorije







Vir: internet

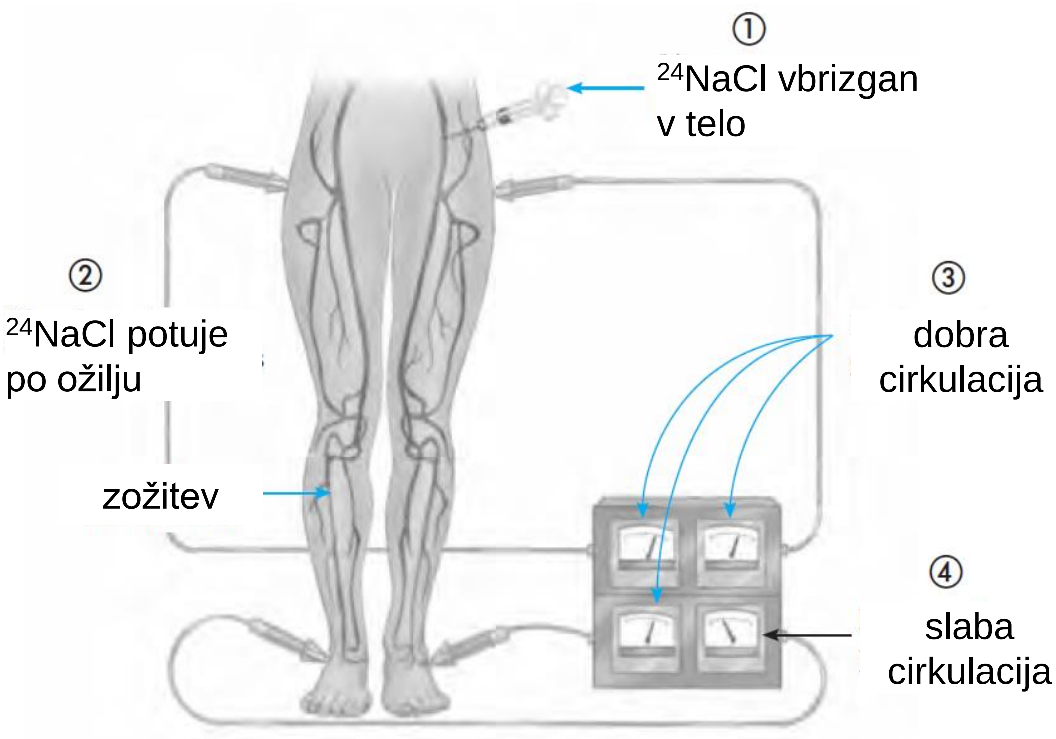
10.7 Posledice, meritve in uporaba radioakt. sevanja

- Uporaba radioaktivnega sevanja:

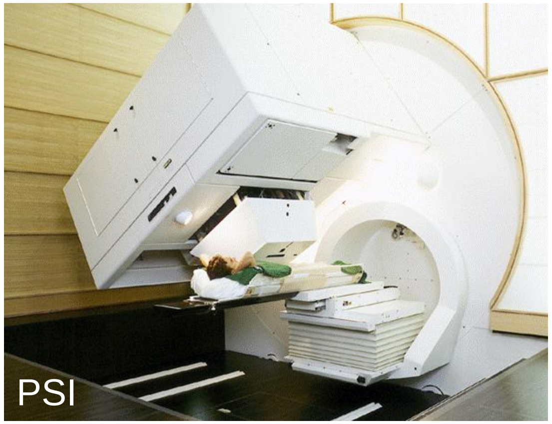
1. Nevtronska aktivacija:

$$ {}^{1}_{0}n + {}^{65}_{29}\mathrm{Cu} \rightarrow {}^{66}_{29}\mathrm{Cu} \rightarrow {}^{66}_{30}\mathrm{Zn} + \mathrm{e}^{-} + \bar{\nu} \quad (t_{1/2} = 5{,}1\,\mathrm{min}) $$

2. Sledenje radioaktivnim izotopom:



3. Radiacijska terapija:



4. Datiranje: razpad izotopa ^{14}C

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \mathrm{e}^{-} + \bar{\nu} \quad (t_{1/2} = 5730\,\mathrm{let}) $$

SIMULACIJA

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

Univerza v Ljubljani
Fakulteta za matematiko in fiziko

MODERNA FIZIKA

Osnovni delci

Andrej Zorko
Fakulteta za matematiko in fiziko, Univerza v Ljubljani

11.1 Fundamentalne sile v naravi

- Sile med delci:

1. močna sila
   - med kvarki in hadroni
   - kratkega dosega (med hadroni)

2. elektromagnetna sila
   - med nabitimi delci
   - dolgega dosega

3. šibka sila
   - med kvarki in leptoni
   - kratkega dosega

4. gravitacijska sila
   - med delci z maso
   - dolgega dosega

Vir: internet

11.1 Fundamentalne sile v naravi

- Kvantna teorija polja: delci polja (umeritveni bozoni)

Interakcija (sila)	Med	Relat. jakost	τ	Doseg	Delci polja
močna	kvarki, hadroni	1	$\leq 10^{-20}$ s	kratek (~1 fm)	gluoni
elektromagnetna	nabiti delci	$\sim 10^{-2}$	$\sim 10^{-16}$ s	dolg (∞)	fotoni
šibka	kvarki, leptoni	$\sim 10^{-6}$	$\geq 10^{-10}$ s	kratek ($\sim 10^{-3}$ fm)	šibki bozoni $W^{\pm}$, Z^0
gravitacijska	vsi delci	$\sim 10^{-43}$	?	dolg (∞)	gravitoni

- Higgsov bozon vs. graviton (kvant gravitacijskega polja):

Vir: internet

11.2 Klasifikacija delcev

- V 1930-ih so poznali 6 delcev:
  - proton
  - nevtron
  - elektron
  - foton
  - nevtrino
  - pozitron

The Nobel Prize in Physics 1936

Victor Franz Hess
Prize share: 1/2

Carl David Anderson
Prize share: 1/2

The Nobel Prize in Physics 1936 was divided equally between Victor Franz Hess *"for his discovery of cosmic radiation"* and Carl David Anderson *"for his discovery of the positron"*.

- Pospeševalniki: novi delci
  - mezoni π
  - mioni

The Nobel Prize in Physics 1950

Cecil Frank Powell
Prize share: 1/1

The Nobel Prize in Physics 1950 was awarded to Cecil Powell *"for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method"*.

Vir: internet

11.2 Klasifikacija delcev

- Delce delimo na:
  1. HADRONI (močna sila)
     - a) mezoni
     - b) barioni
  2. LEPTONI (elektromagnetna in šibka sila)
- Antidelci:

The Nobel Prize in Physics 1959

Emilio Gino Segrè
Prize share: 1/2

Owen Chamberlain
Prize share: 1/2

The Nobel Prize in Physics 1959 was awarded jointly to Emilio Gino Segrè and Owen Chamberlain *"for their discovery of the antiproton"*

Kategorija	Ime	Simbol	Anti-delec	Masa (MeV/c^2)	B	L_e	L_μ	L_τ	S	τ (s) τ	Osnovni razpad
HADRONI Mezoni	Pion	π^+	π^-	139.6	0	0	0	0	0	2.60×10^{-8}	$\mu^+\nu_\mu$
		π^0	Self	135.0	0	0	0	0	0	0.83×10^{-16}	2γ
	Kaon	K^+	K^-	493.7	0	0	0	0	+1	1.24×10^{-8}	$\mu^+\nu_\mu$, $\pi^+\pi^0$
		K_S^0	$\overline{K}_S^0$	497.7	0	0	0	0	+1	0.89×10^{-10}	$\pi^+\pi^-$, $2\pi^0$
		K_L^0	$\overline{K}_L^0$	497.7	0	0	0	0	+1	5.2×10^{-8}	$\pi^\pm e^\mp \overline{\nu}_e$, $3\pi^0$, $\pi^\pm\mu^\mp\overline{\nu}_\mu$
	Eta	η	Self	548.8	0	0	0	0	0	$<10^{-18}$	2γ, $3\pi^0$
		η'	Self	958	0	0	0	0	0	2.2×10^{-21}	$\eta\pi^+\pi^-$
Barioni	Proton	p	$\overline{p}$	938.3	+1	0	0	0	0	Stable	
	Neutron	n	$\overline{n}$	939.6	+1	0	0	0	0	624	$pe^-\overline{\nu}_e$
	Lambda	Λ^0	$\overline{\Lambda}^0$	1115.6	+1	0	0	0	−1	2.6×10^{-10}	$p\pi^-$, $n\pi^0$
	Sigma	Σ^+	$\overline{\Sigma}^-$	1189.4	+1	0	0	0	−1	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
		Σ^0	$\overline{\Sigma}^0$	1192.5	+1	0	0	0	−1	6×10^{-20}	$\Lambda^0\gamma$
		Σ^-	$\overline{\Sigma}^+$	1197.3	+1	0	0	0	−1	1.5×10^{-10}	$n\pi^-$
	Delta	Δ^{++}	$\overline{\Delta}^{--}$	1230	+1	0	0	0	0	6×10^{-24}	$p\pi^+$
		Δ^+	$\overline{\Delta}^-$	1231	+1	0	0	0	0	6×10^{-24}	$p\pi^0$, $n\pi^+$
		Δ^0	$\overline{\Delta}^0$	1232	+1	0	0	0	0	6×10^{-24}	$n\pi^0$, $p\pi^-$
		Δ^-	$\overline{\Delta}^+$	1234	+1	0	0	0	0	6×10^{-24}	$n\pi^-$
	Xi	Ξ^0	$\overline{\Xi}^0$	1315	+1	0	0	0	−2	2.9×10^{-10}	$\Lambda^0\pi^0$
		Ξ^-	Ξ^+	1321	+1	0	0	0	−2	1.64×10^{-10}	$\Lambda^0\pi^-$
	Omega	Ω^-	Ω^+	1672	+1	0	0	0	−3	0.82×10^{-10}	$\Xi^-\pi^0$, $\Xi^0\pi^-$, $\Lambda^0 K^-$
LEPTONI	Electron	e^-	e^+	0.511	0	+1	0	0	0	Stable	
	Electron-neutrino	ν_e	$\overline{\nu}_e$	$<2.8 \times 10^{-6}$	0	+1	0	0	0	Stable	
	Muon	μ^-	μ^+	105.7	0	0	+1	0	0	2.19×10^{-6}	$e^-\overline{\nu}_e\nu_\mu$
	Muon-neutrino	ν_μ	$\overline{\nu}_\mu$	$<3.5 \times 10^{-6}$	0	0	+1	0	0	Stable	
	Tau	τ^-	τ^+	1784	0	0	0	+1	0	3.3×10^{-13}	$\mu^-\overline{\nu}_\mu\nu_\tau$, $e^-\overline{\nu}_e\nu_\tau$
	Tau-neutrino	ν_τ	$\overline{\nu}_\tau$	$<8.4 \times 10^{-6}$	0	0	0	+1	0	Stable	

Vir: internet; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

11.2 Klasifikacija delcev

Nevtrinske oscilacije:

- Deficit sončnih elektronskih nevtrinov

$$ {}^1_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{H} + e^+ + \nu_e $$

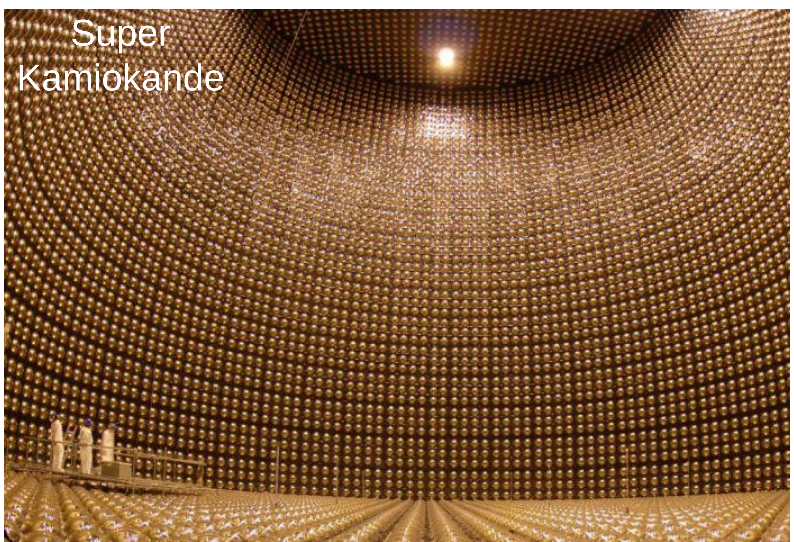
- Mešanje nevtrinov:

matrika PMNS

$$ |\nu_\alpha\rangle = \sum_i U^*_{\alpha,i} |\nu_i\rangle $$

dober okus

dobra masa



Vir: internet

The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

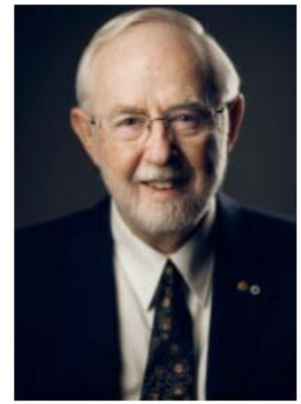


Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

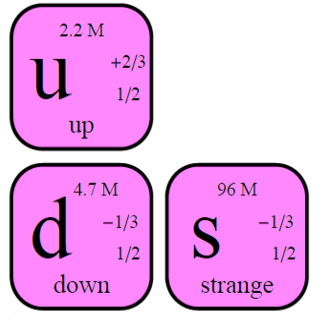
11.3 Kvarkovska sestava hadronov

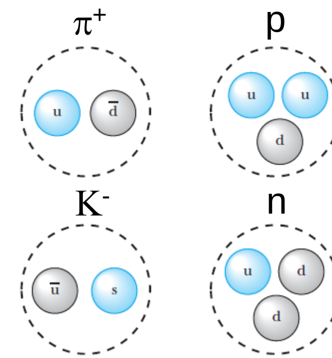
- Kvarkovski model:

  a) mezon = kvark/antikvark

  b) barioni = 3 kvarki

  vezivo = gluoni



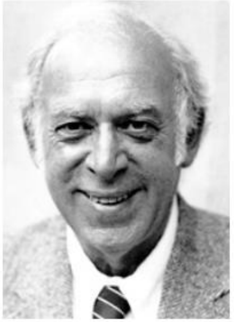


The Nobel Prize in Physics 1969

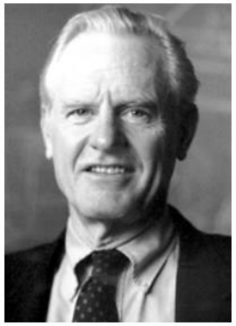
Murray Gell-Mann
Prize share: 1/1

The Nobel Prize in Physics 1969 was awarded to Murray Gell-Mann *"for his contributions and discoveries concerning the classification of elementary particles and their interactions"*.

The Nobel Prize in Physics 1990



Jerome I. Friedman
Prize share: 1/3



Henry W. Kendall
Prize share: 1/3

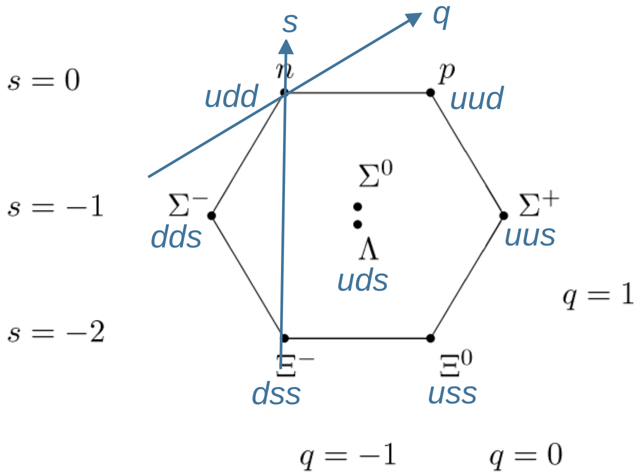
Photo: T. Nakashima
Richard E. Taylor
Prize share: 1/3

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"*.

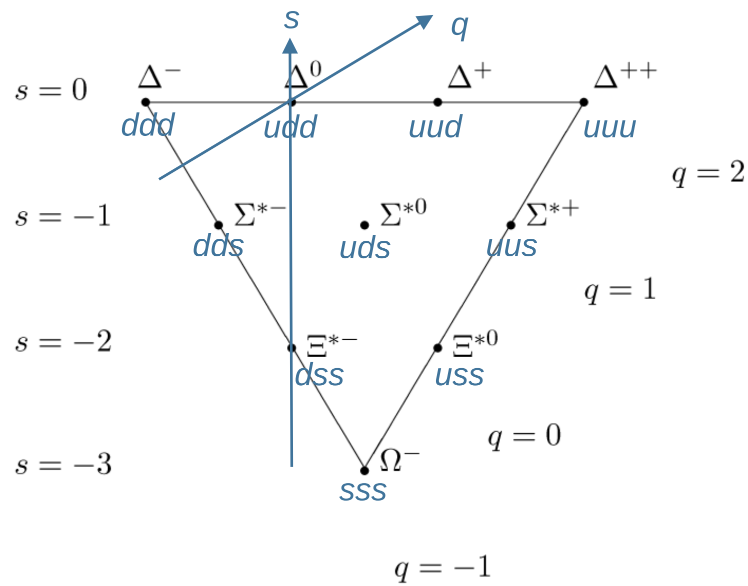
Vir: internet; ; povzeto po Serway, Moses & Moyer, Modern Physics, Thomson Learning, 2005

11.3 Kvarkovska sestava hadronov

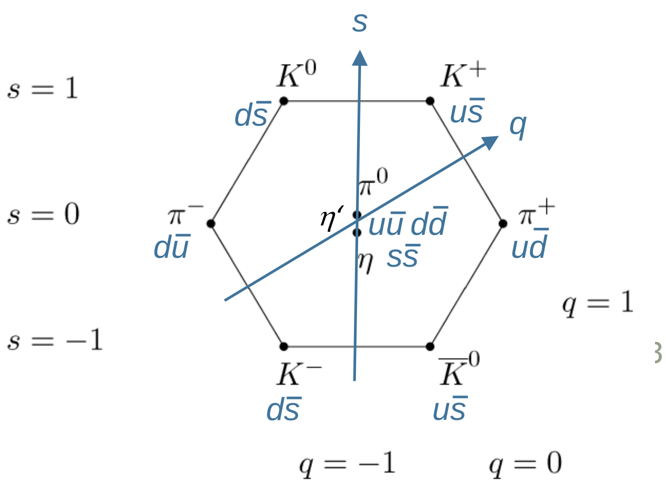
- Barionski oktet (spin 1/2)



- Barionski dekuplet (spin 3/2)

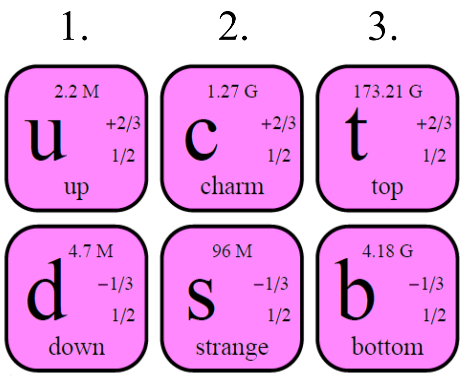


- Mezonski nonet = oktet + singlet (spin 0)



11.3 Kvarkovska sestava hadronov

- 3 družine kvarkov:



The Nobel Prize in Physics 2008

Photo: University of Chicago
Yoichiro Nambu
Prize share: 1/2

© The Nobel Foundation
Photo: U. Montan
Makoto Kobayashi
Prize share: 1/4

© The Nobel Foundation
Photo: U. Montan
Toshihide Maskawa
Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

Kvark	Simbol	Spin	Naboj	Barionsko število	Čudnost	Šarm	Dno	Vrh
Up	u	$\frac{1}{2}$	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	0
Down	d	$\frac{1}{2}$	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	0	0
Strange	s	$\frac{1}{2}$	$-\frac{1}{3}e$	$\frac{1}{3}$	-1	0	0	0
Charmed	c	$\frac{1}{2}$	$+\frac{2}{3}e$	$\frac{1}{3}$	0	$+1$	0	0
Bottom	b	$\frac{1}{2}$	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	$+1$	0
Top	t	$\frac{1}{2}$	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	$+1$

Vir: internet

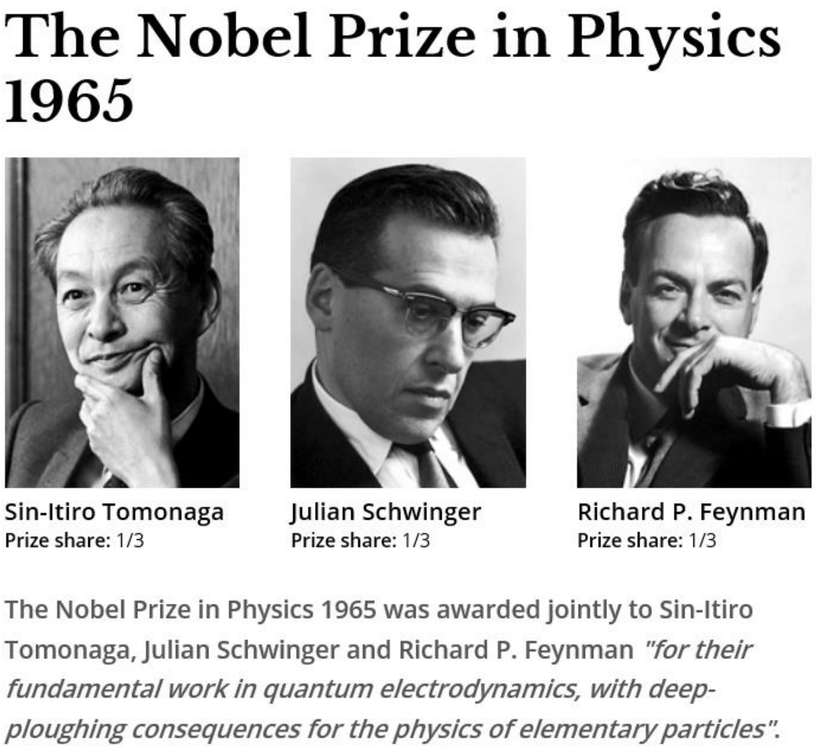
- Kvantna kromodinamika: barvni naboj (močna sila)

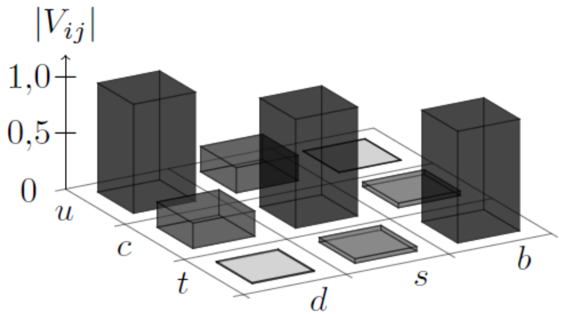
$$\psi = \psi_r \psi_S \psi_o \psi_{bn}$$

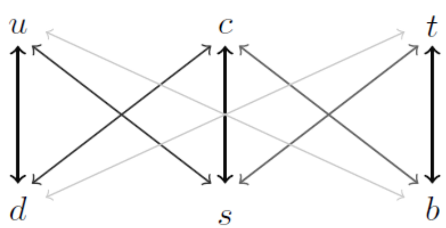
- Mešanje kvarkov (šibka sila): matrika Cabbibo-Kobayashi-Maskawa

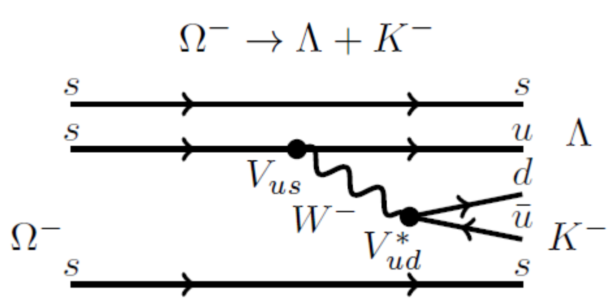
$$|V_{\mathrm{CKM}}| = \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix}$$

$$= \begin{bmatrix} 0{,}97428 & 0{,}2253 & 0{,}00347 \\ 0{,}2252 & 0{,}97345 & 0{,}0410 \\ 0{,}00862 & 0{,}0403 & 0{,}999152 \end{bmatrix}$$









Vir: internet

- Elektrošibka interakcija:

The Nobel Prize in Physics 1984

Carlo Rubbia
Prize share: 1/2

Simon van der Meer
Prize share: 1/2

The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*

The Nobel Prize in Physics 1979

Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

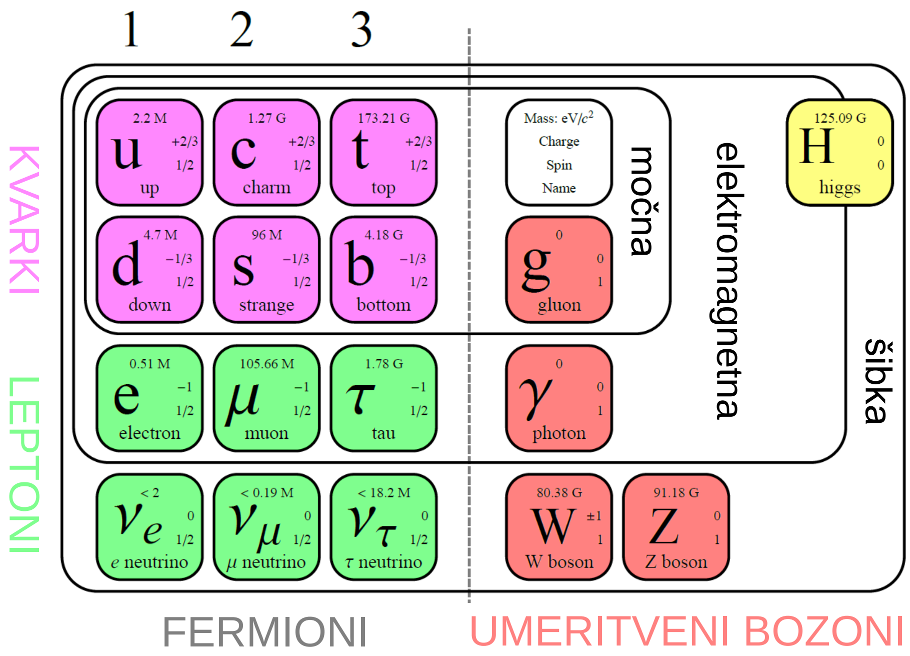
Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Vir: internet

11.4 Standardni model

- Standardni model:



The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

SIMULACIJA

Vir: internet

11.5 Ohranitveni zakoni in Feynmanovi diagrami

- Ohranitveni zakoni:

Zvezne transformacije:

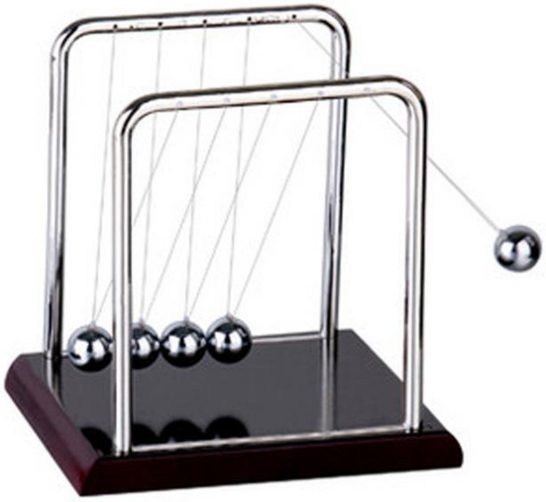
1. ohranitev energije (premik časa)
2. ohranitev gibalne količine (premik v prostoru)
3. ohranitev vrtilne količine (zasuk v prostoru)

Nezvezne transformacije:

4. ohranitev parnosti (inverzija prostora)
5. invariantnost na inverzijo prostora
6. Invariantnost na konjugacijo naboja

Empirični zakoni:

7. ohranitev barionskega števila
8. ohranitev leptonskih števil
9. ohranitev okusnega naboja
10. ohranitev naboja



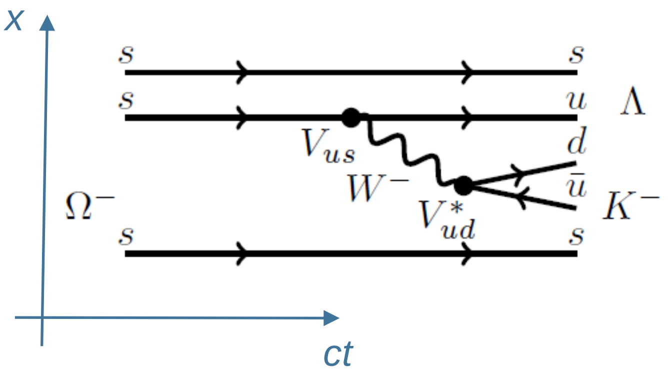
- Šibka sila krši: 4, 5, 6, 9

Vir: internet

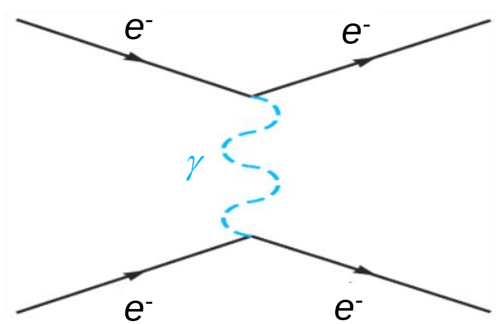
11.5 Ohranitveni zakoni in Feynmanovi diagrami

- Feynmanovi diagrami:

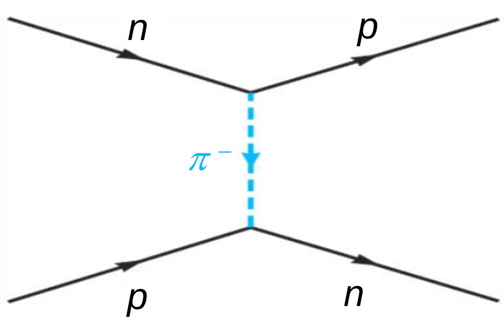
  1. svetovnice
  2. temena

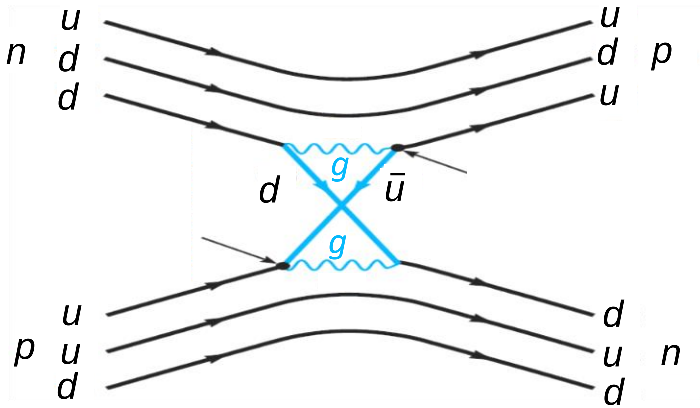


Elektromagnetna sila:



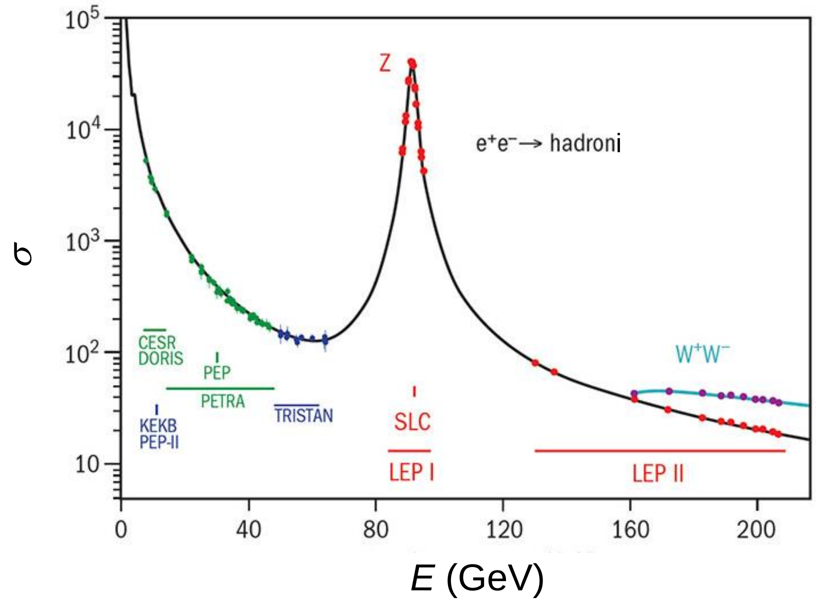
Močna sila:





11.6 Produkcija osnovnih delcev

- Resonance v sipalnem preseku:



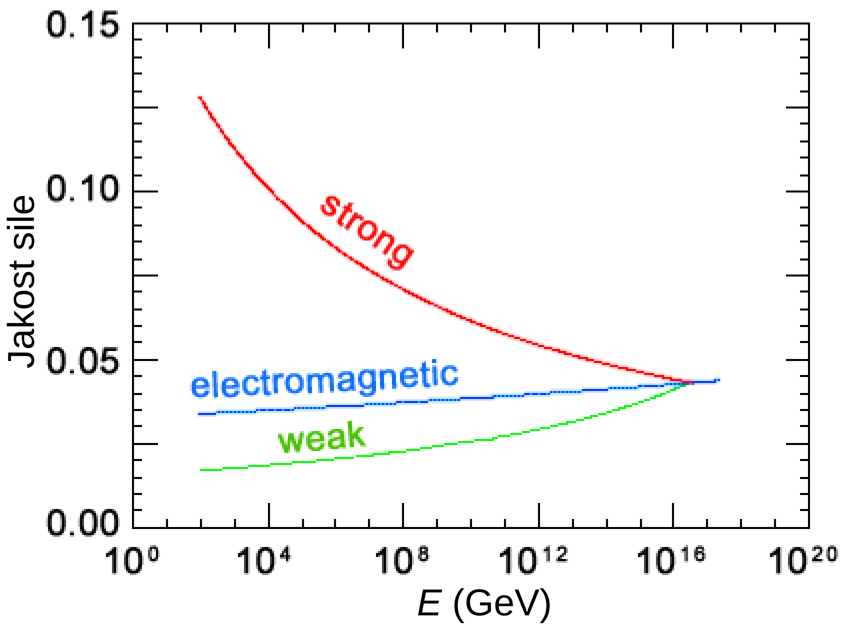
- Pospeševalniki, trkalniki

Pospeševalnik	Kraj	Obratovanje	Pospešeni delci	Maksimalna E GeV	Svetlost, 10^{30} cm^{-2} s^{-1}	Premer km
VEPP-2000	INP, Novosibirsk, Russia	2006	e^+e^-	1.0	100	0.024
VEPP-4M	INP, Novosibirsk, Russia	1994	e^+e^-	6	20	0.366
BEPC II	IHEP, Beijing, China	2008	e^+e^-	3.7	700	0.240
DAFNE	Frascati, Italy	1999	e^+e^-	0.7	436[12]	0.098
KEKB/SuperKEKB	KEK, Tsukuba, Japan	1999	e^+e^-	8.5 (e-), 4 (e+)	21100	3.016
RHIC	BNL, United States	2000	pp, Au-Au, Cu-Cu, d-Au	100/n	10, 0.005, 0.02, 0.07	3.834
LHC	CERN	2008	pp, Pb-Pb, p-Pb, Xe-Xe	6500 (plan 7000), 2560/n (plan 2760/n)	20000[13], 0.003, 0.9, ~0.0002	26.659

Vir: internet

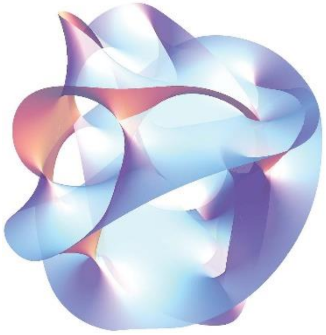
11.7 Onstran standardnega modela

- Velika teorija poenotenja = elektrošibka teorija + kvantna kromodinamika
  - velika poenotena sila
  - leptokvark (kvark, lepton)
  - supersimetrija (fermion ↔ bozon)



- Teorija strun
  - poenotena vseh štirih fundamentalnih sil
  - delec = vibracija strune
  - 10 dimenzij
  - več verzij teorije superstrun

„kompaktifikacija“



struni

Vir: internet

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