

# ВЗАИМОДЕЙСТВИЕ ИОНИЗИРУЮЩЕГО ИЗЛУЧЕНИЯ С ВЕЩЕСТВОМ

АВТОР ПРЕЗЕНТАЦИИ: СТАРШИЙ ПРЕПОДАВАТЕЛЬ  
КАФЕДРЫ ЯИРБ, БОГАЧЁВА Е.С.

# СТАНДАРТНАЯ МОДЕЛЬ

## THE STANDARD MODEL OF FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

### FERMIONS

matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_L$ lightest neutrino*	$(0-2) \times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_M$ middle neutrino*	$(0.009-2) \times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_H$ heaviest neutrino*	$(0.05-2) \times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

\*See the neutrino paragraph below.

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

**The energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ) where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$  joule. The mass of the proton is 0.938 GeV/c<sup>2</sup> =  $1.67 \times 10^{-27}$  kg.

#### Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states  $\nu_e$ ,  $\nu_\mu$  or  $\nu_\tau$ , labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

#### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$  but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

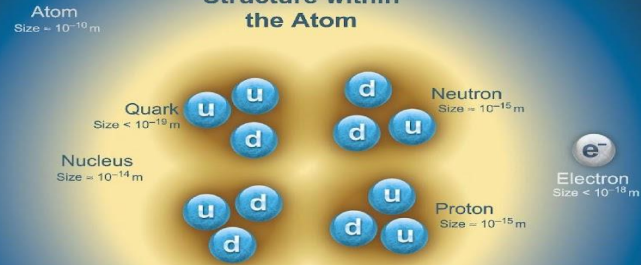
### Particle Processes

These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron  $\beta$  (beta) decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce  $B^0$  and  $B^0$  mesons via a virtual Z boson or a virtual photon.

### Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

### BOSONS

force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
<b>W<sup>-</sup></b>	80.39	-1
<b>W<sup>+</sup></b>	80.39	+1
<b>Z<sup>0</sup></b>	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>g</b> gluon	0	0

Higgs Boson spin = 0		
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>H</b> Higgs	126	0

#### Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

#### Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

#### Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated — they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature mesons  $q\bar{q}$  and baryons  $qqq$ . Among the many types of baryons observed are the proton (uud), antiproton ( $\bar{u}\bar{u}\bar{d}$ ), and neutron (udd). Quark charges add in such a way as to make the proton have charge +1 and the neutron charge 0. Among the many types of mesons are the pion  $\pi^+$  ( $u\bar{d}$ ), kaon  $K^-$  ( $s\bar{u}$ ), and  $B^0$  ( $d\bar{s}$ ).

Learn more at [ParticleAdventure.org](http://ParticleAdventure.org)



### Properties of the Interactions

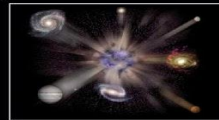
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	<b>W<sup>+</sup> W<sup>-</sup> Z<sup>0</sup></b>	$\gamma$	Gluons
Strength at $\left\{ \begin{array}{l} 10^{-16} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{array} \right.$	$10^{-41}$ $10^{-41}$	0.8 $10^{-4}$	1 1	25 60

### Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

#### Why is the Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

#### Why No Antimatter?



Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

#### What is Dark Matter?



Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

#### Are there Extra Dimensions?



An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paperclip overwhelming Earth's gravity).



# ВИДЫ ИОНИЗИРУЮЩЕГО ИЗЛУЧЕНИЯ

## Charged Particulate Radiations

Heavy charged particles  
(characteristic distance  $\cong 10^{-5}$  m)

Fast electrons  
(characteristic distance  $\cong 10^{-3}$  m)

## Uncharged Radiations

Neutrons  
(characteristic length  $\cong 10^{-1}$  m)

X-rays and gamma rays  
(characteristic length  $\cong 10^{-1}$  m)

Тяжелые заряженные частицы  
(характерный пробег  $10^{-5}$  м)

Легкие заряженные частицы  
(характерный пробег  $10^{-3}$  м)

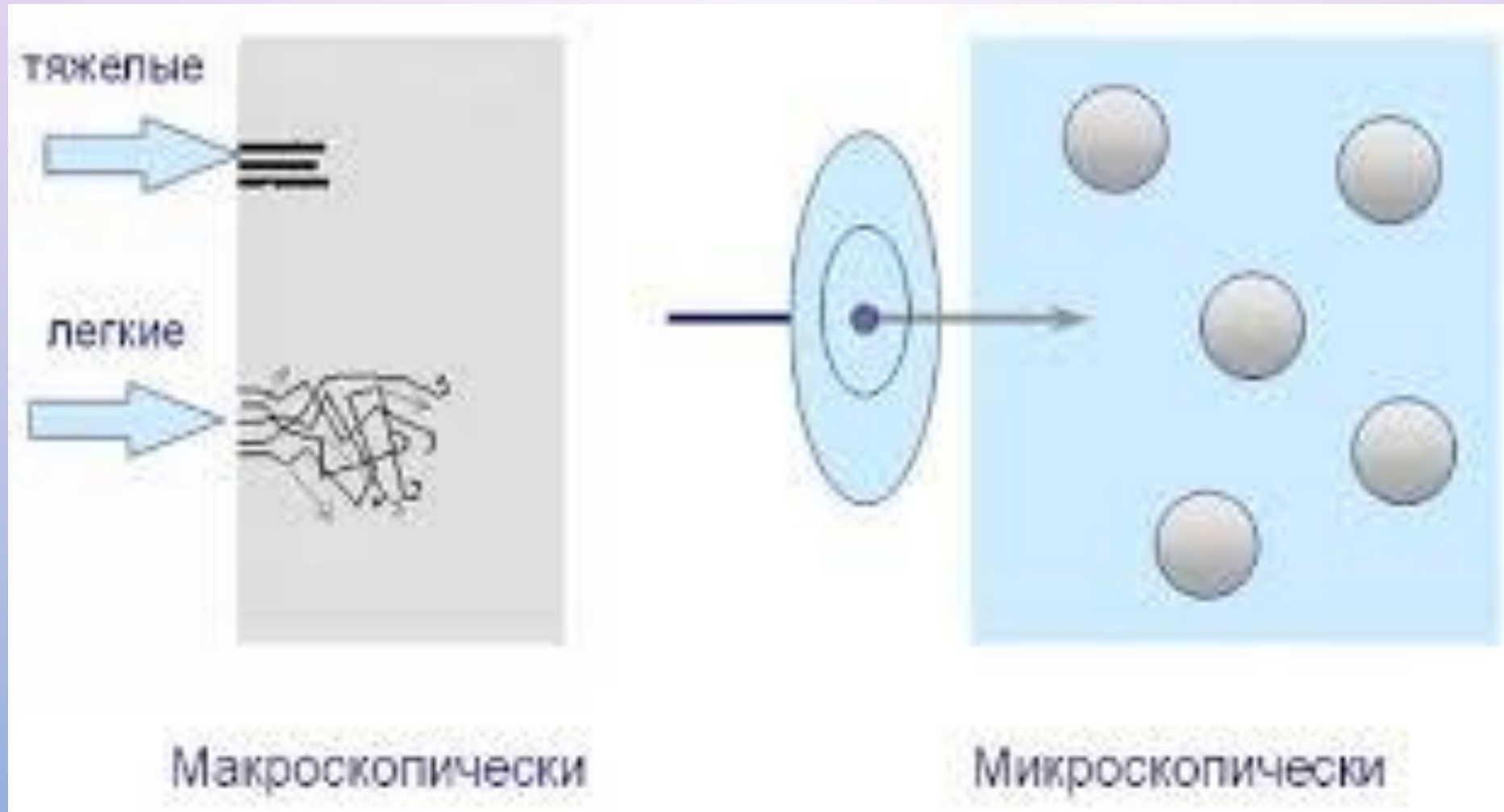
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Нейтроны  
(характерная длина  $10^{-1}$  м)

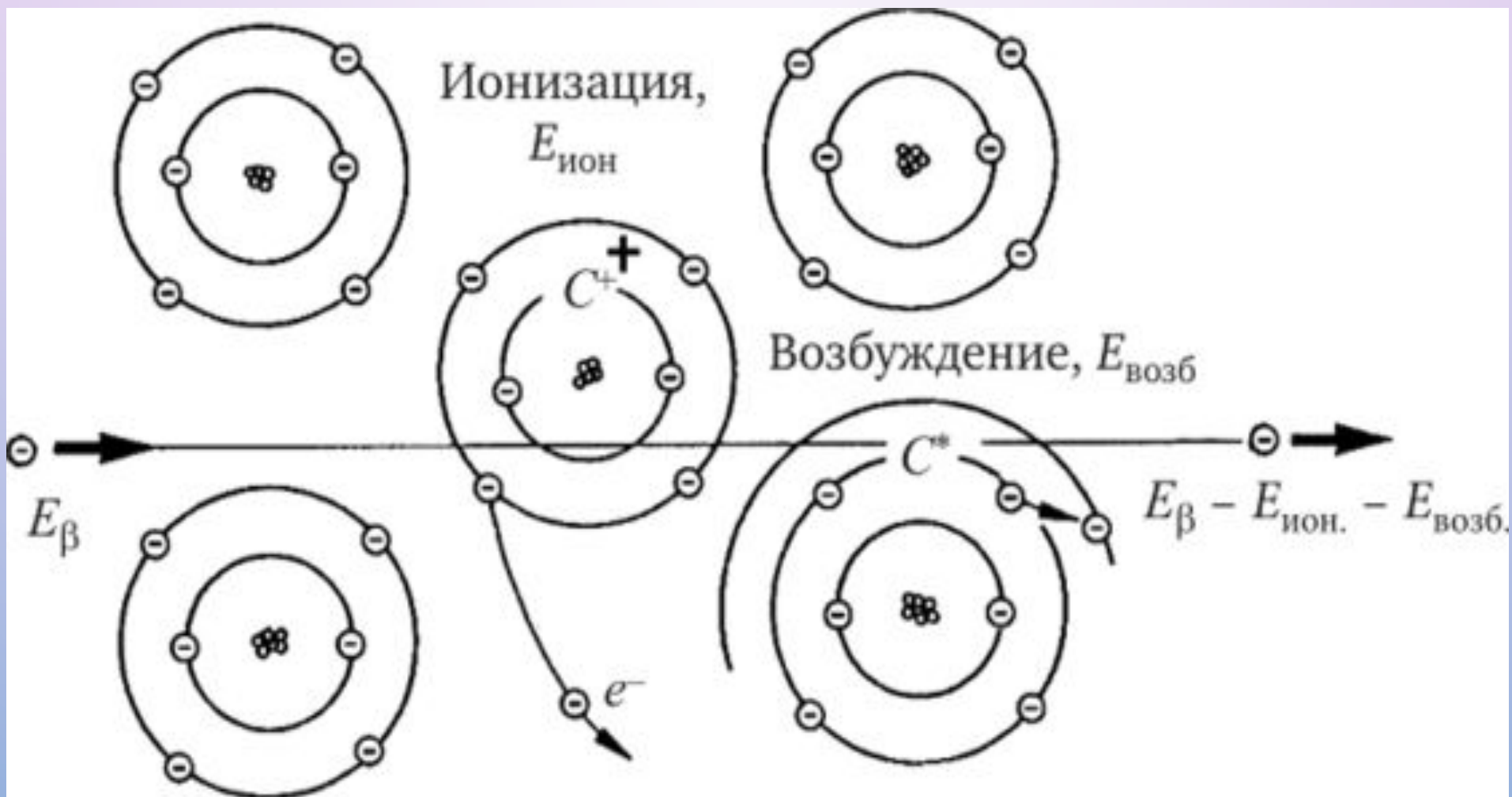
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Рентгеновское и гамма-излучение  
( $10^{-1}$  м)

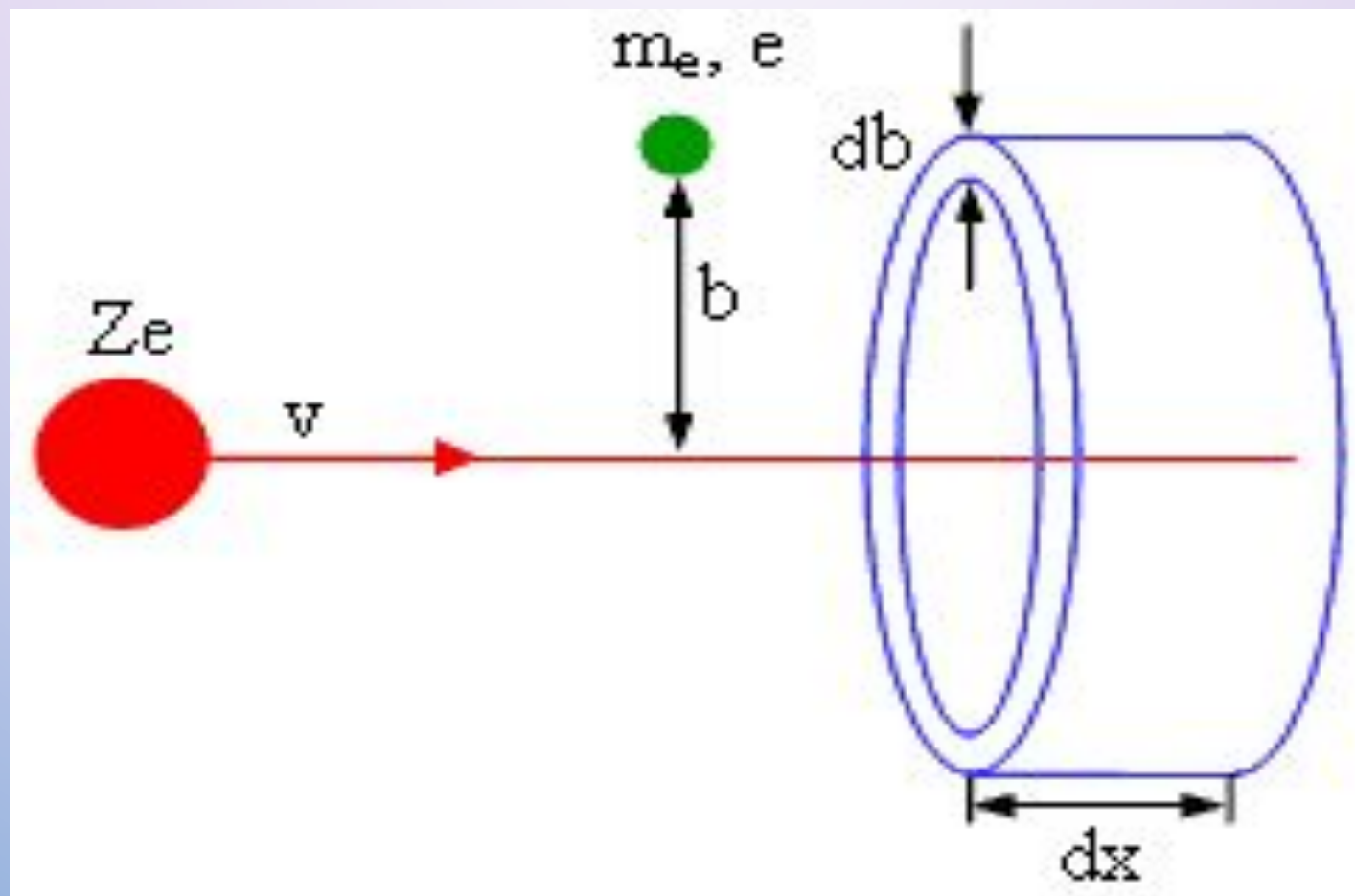
# СХЕМАТИЧЕСКИЕ ТРАЕКТОРИИ ДВИЖЕНИЯ ТЯЖЕЛЫХ И ЛЕГКИХ ЗАРЯЖЕННЫХ ЧАСТИЦ В ВЕЩЕСТВЕ



# ПРОЦЕССЫ ИОНИЗАЦИИ И ВОЗБУЖДЕНИЯ



# ИЛЛЮСТРАЦИЯ К ПОНЯТИЮ ПРИЦЕЛЬНОГО ПАРАМЕТРА



# УДЕЛЬНЫЕ ПОТЕРИ ЭНЕРГИИ. ФОРМУЛА БЕТЕ.

$$S = -\frac{dE}{dx}$$

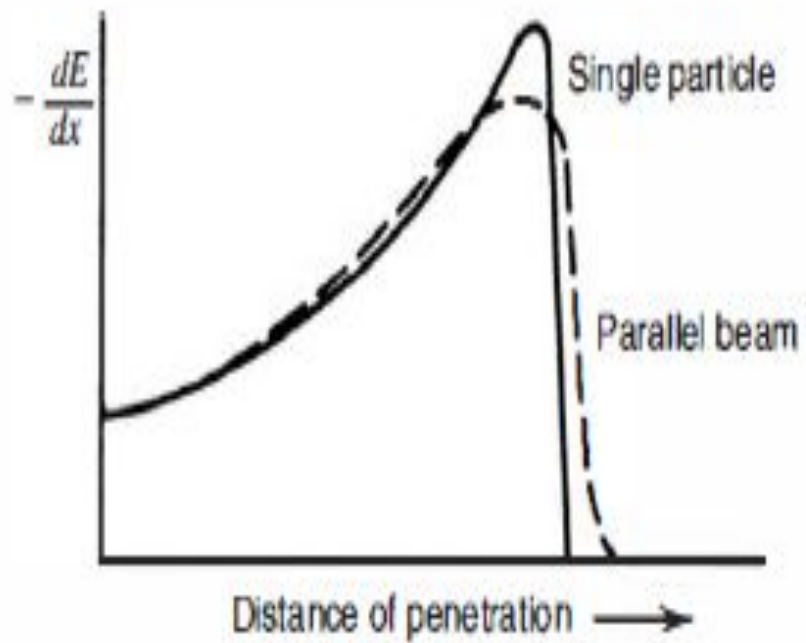
$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} NB$$

where

$$B \equiv Z \left[ \ln \frac{2m_0 v^2}{I} - \ln \left( 1 - \frac{v^2}{c^2} \right) - \frac{v^2}{c^2} \right]$$



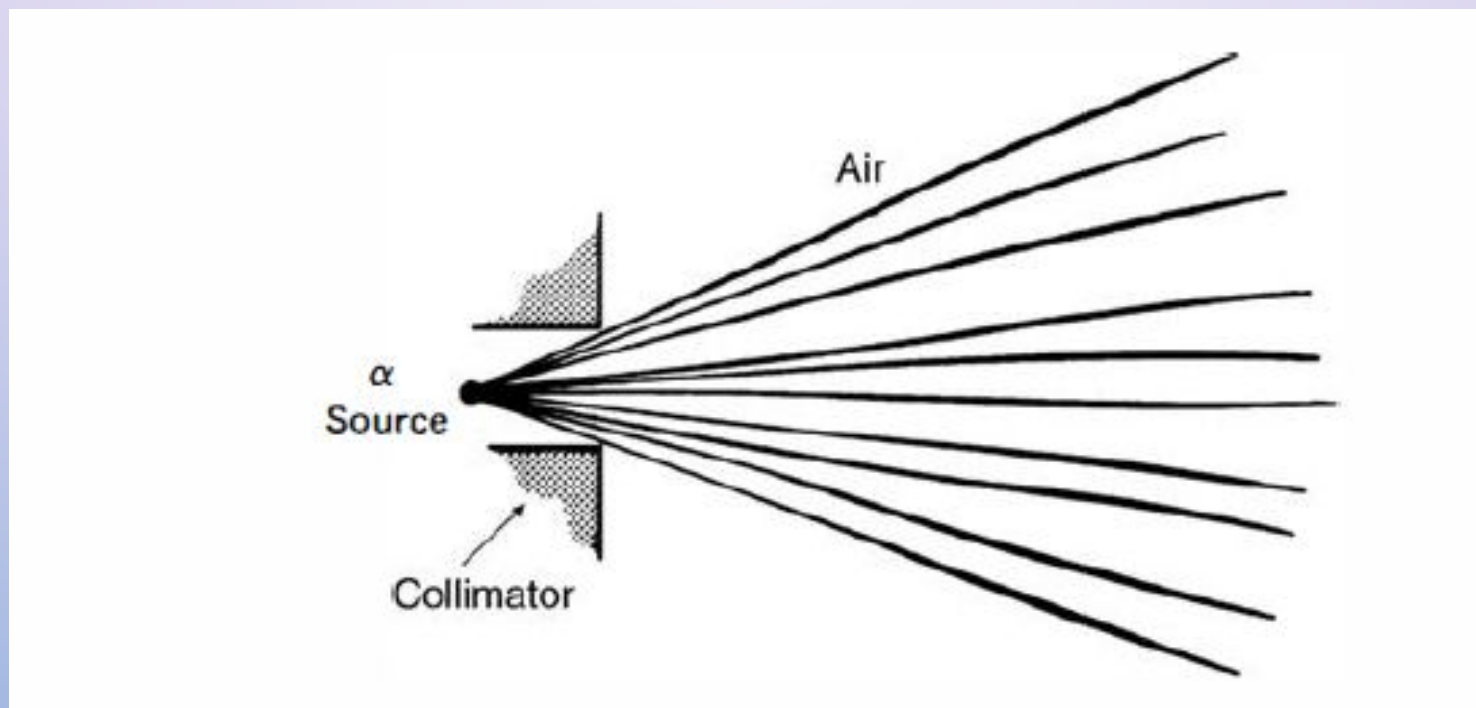
# КРИВАЯ БРЭГГА



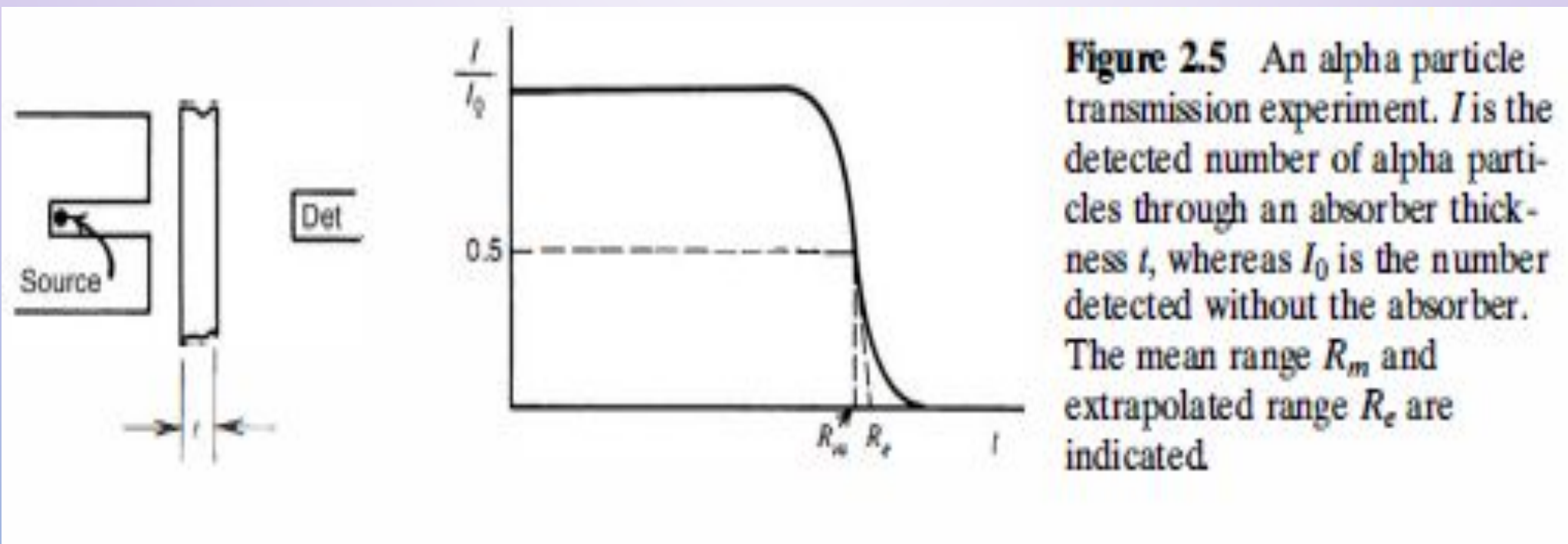
**Figure 2.2** The specific energy loss along an alpha track.



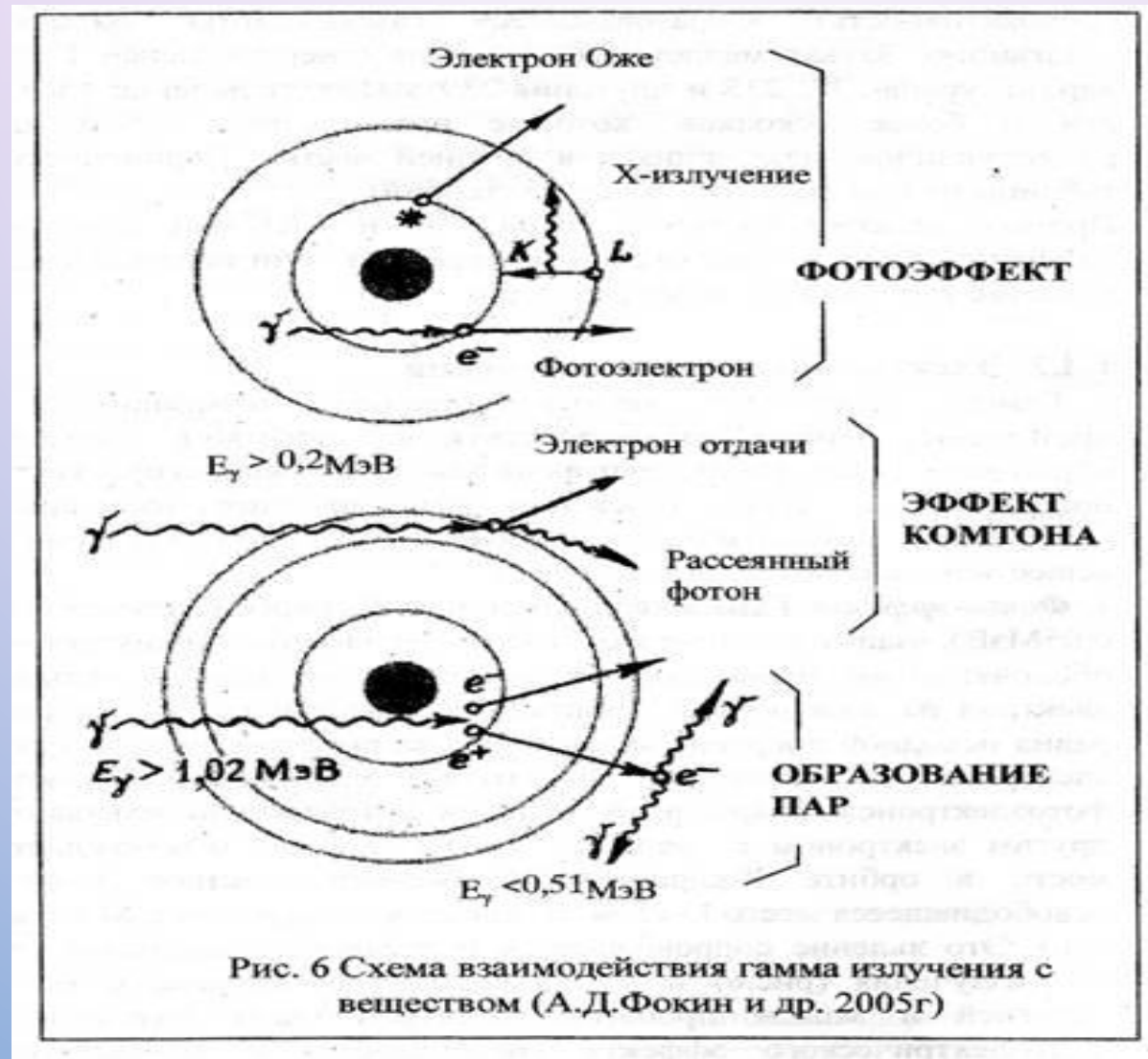
# КОЛЛИМИРОВАННЫЙ ПУЧОК АЛЬФА-ЧАСТИЦ



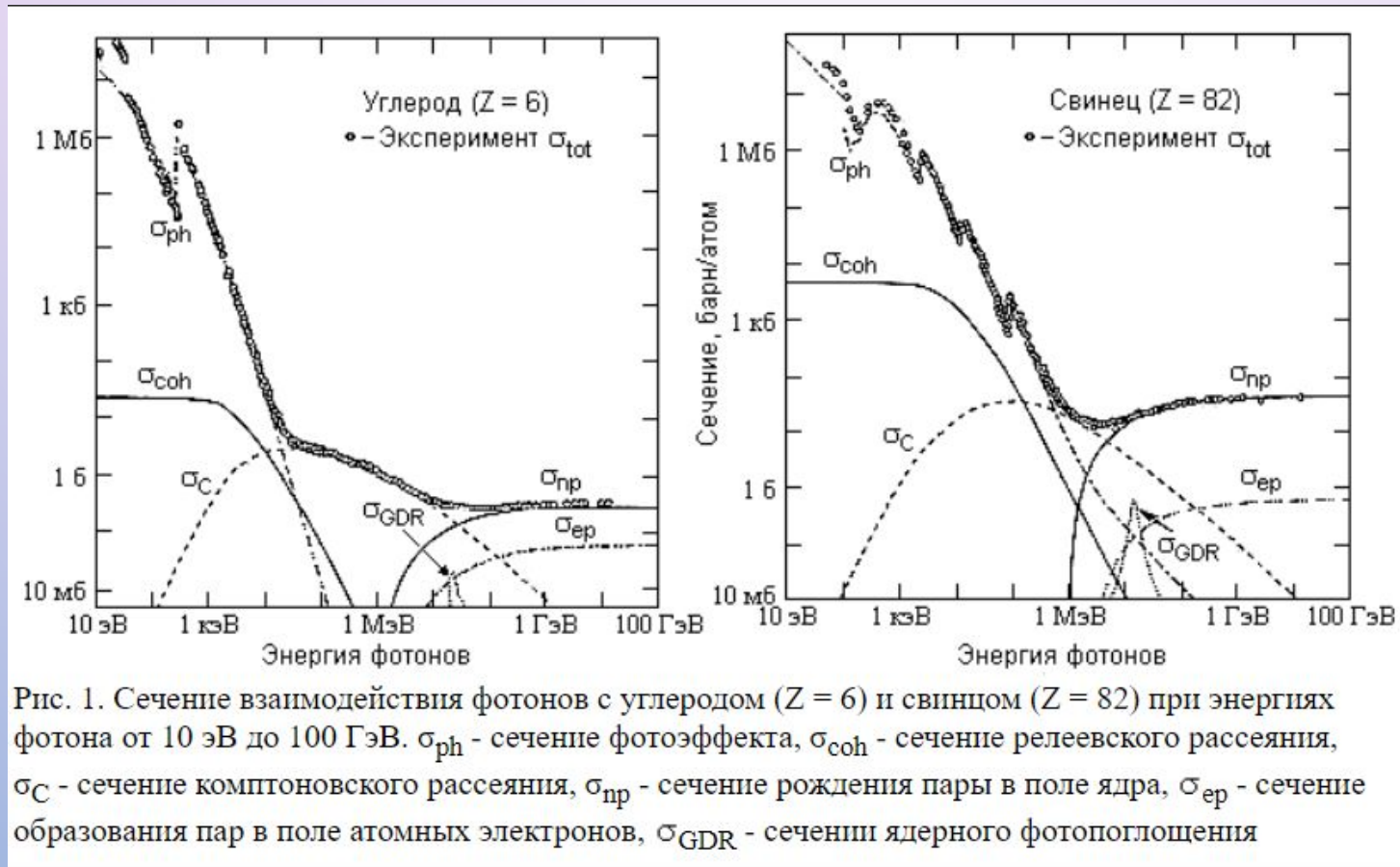
# ОПРЕДЕЛЕНИЕ МАКСИМАЛЬНОГО ПРОБЕГА АЛЬФА-ЧАСТИЦ В ВЕЩЕСТВЕ



# ПРОЦЕССЫ ВЗАИМОДЕЙСТВИЯ ГАММА-ИЗЛУЧЕНИЯ С ВЕЩЕСТВОМ



# СЕЧЕНИЯ ВЗАИМОДЕЙСТВИЯ





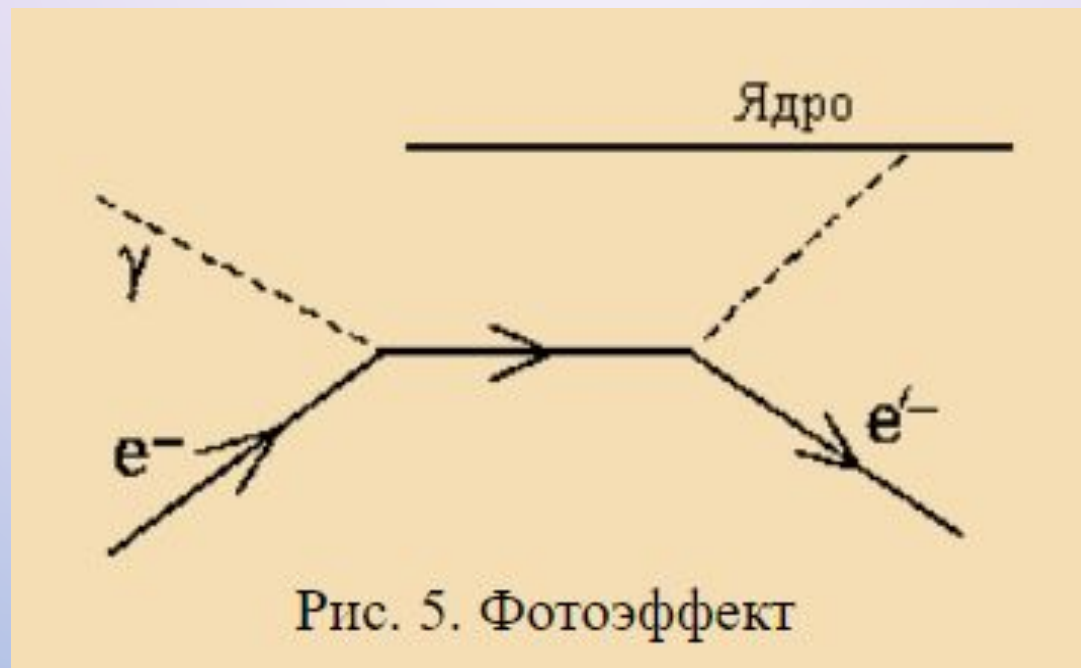
# ФОТОЭФФЕКТ

$$E_e = E_\gamma - I_i - E_n, \quad (3)$$

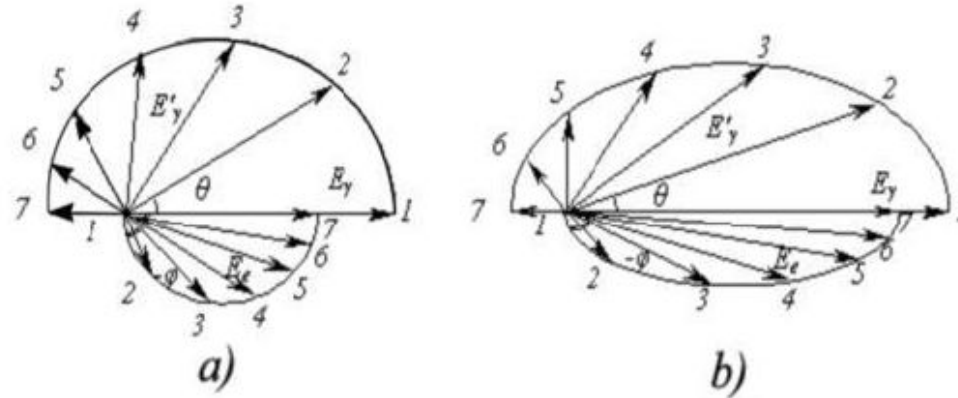
$I_i$  – ионизационный потенциал оболочки атома, из которой выбивается электрон;  $E_n$  – энергия отдачи ядра,  $E_\gamma$  – энергия гамма-кванта. Величина энергии отдачи ядра обычно мала, поэтому ею можно пренебречь. Тогда энергия фотоэлектрона определится соотношением  $E_e = E_\gamma - I_i$ , где  $i = K, L, M, \dots$  – индекс электронной оболочки.

$$\sigma_{ph} \sim Z^5$$

# ДИАГРАММА ФЕЙНМАНА ДЛЯ ФОТОЭФФЕКТА



# КОМПТОН-ЭФФЕКТ

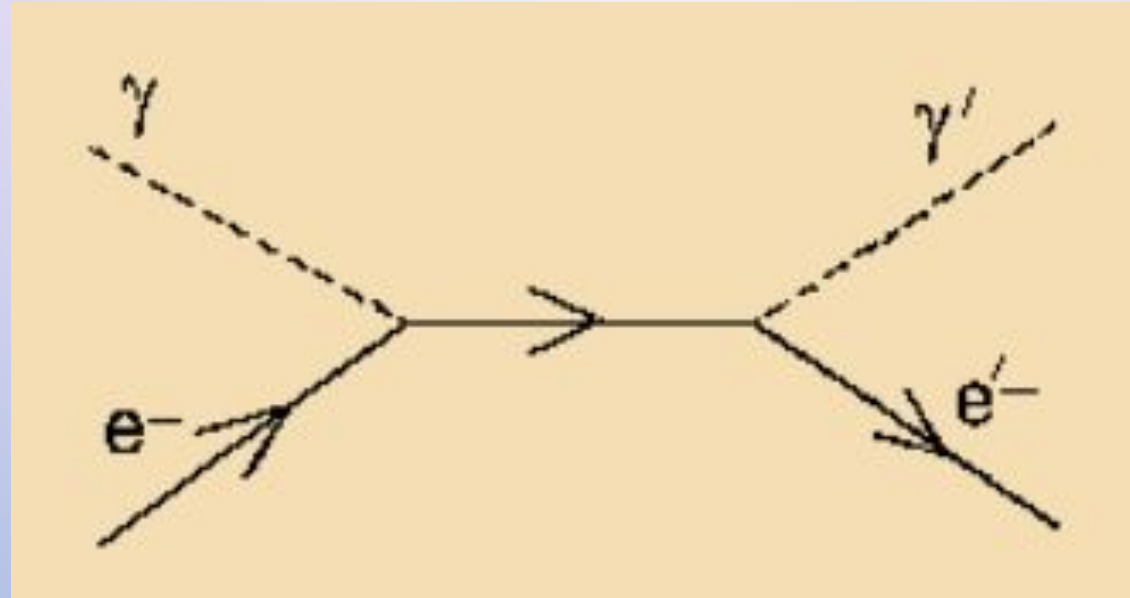


*Рис. 2.8. Полярные диаграммы рассеяния фотонов на свободных электронах, где а)  $E_\gamma=0,64$  МэВ; б)  $E_\gamma=2.55$  МэВ*

$$\vec{P}_\gamma = \vec{P}'_\gamma + \vec{P}_e, \quad m_e c^2 + \underline{E_\gamma} = \underline{E'_\gamma} + \underline{E_e},$$

где  $m_e c^2 = 0.511$  МэВ – энергия покоя электрона,  $E_e$  – полная энергия электрона,  $E_\gamma$  и  $E'_\gamma$  – энергии падающего и рассеянного  $\gamma$ -квантов.

# ДИАГРАММА ФЕЙНМАНА ДЛЯ КОМПТОН-ЭФФЕКТА





# КОМПТОН-ЭФФЕКТ

$$\lambda' - \lambda = \lambda_0(1 - \cos\theta),$$

где  $\lambda'$  и  $\lambda$  – длины волн первичного и рассеянного  $\gamma$ -кванта;  $\lambda_0 = h/m_e c$  – комптоновская длина волны электрона;  $\theta$  - угол между направлениями импульсов  $\vec{P}_\gamma$  и  $\vec{P}'_\gamma$  падающего и рассеянного  $\gamma$ -квантов

# ОБРАЗОВАНИЕ ПАРЫ ЭЛЕКТРОН-ПОЗИТРОН

$$E_{\gamma} \geq 2m_e c^2 + E_{я},$$

где первый член справа соответствует энергии покоя пары электрон-позитрон, а второй – энергия отдачи ядра. Так как энергия отдачи ядра сравнительно мала, то энергия, определяемая первым членом, является порогом рождения пар ( $2m_e c^2 \approx 1.022$  МэВ).

$$\sigma_{пр} \sim Z^2$$

# ДИАГРАММА ФЕЙНМАНА ДЛЯ ОБРАЗОВАНИЯ ПАРЫ ЭЛЕКТРОН-ПОЗИТРОН

